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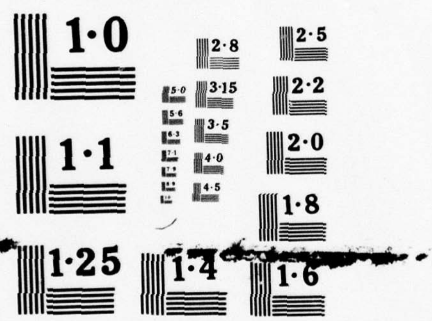
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Report No: FAA-RD-77-189, III

GENERAL AVIATION AIRPLANE STRUCTURAL CRASHWORTHINESS USER'S MANUAL

VOLUME III

RELATED DESIGN INFORMATION

Gil Wittlin

February 1978

Final Report

Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161.

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16. Abstract

This report contains Volume III of the General Aviation Airplane Structural Crashworthiness User's Manual. General information is presented in this report to assist the general aviation airplane industry designer in developing improved structural crashworthiness designs. This report is initiated for the purpose of providing the General Aviation Manufacturers Association (GAMA) members with the basis for understanding the types of procedures, methods and data that are available with regard to structural crashworthiness. This document contains the following sections:

1. General Aviation Airplane Operational and Structural Characteristics;
2. Crash Environment;
3. Occupant Injury Assessment;
4. Structural Data and Methods; and
5. Structural Crashworthiness Design and Compliance Methods.

Each section has its own numbering and reference system, thus, it can be readily updated to include revised or additional information, as such data becomes available. The information presented in this Volume is intended to compliment the KRASH User's Manual (Volume 1) as well as other analytical or test methods that are applicable to structural crashworthiness design.

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METRIC CONVERSION FACTORS

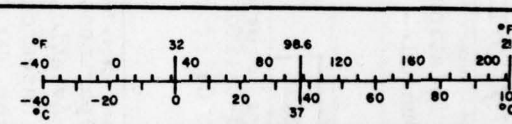
Approximate Conversions to Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
in	inches	*2.5	centimeters	cm
ft	feet	30	centimeters	cm
yd	yards	0.9	meters	m
mi	miles	1.6	kilometers	km
		AREA		
in^2	square inches	6.5	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.8	square meters	m^2
mi^2	square miles	2.6	square kilometers	km^2
	acres	0.4	hectares	ha
		MASS (weight)		
oz	ounces	28	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.9	tonnes	t
		VOLUME		
tsp	teaspoons	5	milliliters	ml
Tbsp	tablespoons	15	milliliters	ml
fl oz	fluid ounces	30	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.8	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

*1 in ≡ 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

Approximate Conversions from Metric Measures

Symbol	When You Know	Multiply by	To Find	Symbol
		LENGTH		
mm	millimeters	0.04	inches	in
cm	centimeters	0.4	inches	in
m	meters	3.3	feet	ft
m	meters	1.1	yards	yd
km	kilometers	0.6	miles	mi
		AREA		
cm^2	square centimeters	0.16	square inches	in^2
m^2	square meters	1.2	square yards	yd^2
km^2	square kilometers	0.4	square miles	mi^2
ha	hectares (10,000 m^2)	2.5	acres	
		MASS (weight)		
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	
		VOLUME		
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.1	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	35	cubic feet	ft^3
m^3	cubic meters	1.3	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



FOREWORD

This report was prepared by the Lockheed-California Company under Contract DOT-FA75-WA-3707. The report contains a partial description of the effort performed as part of Task II and covers the period from July 1976 to December 1977. The work was administered under the direction of the Federal Aviation Administration with H. Spicer acting as Technical monitor.

The program leader was Gil Wittlin of the Lockheed-California Company. Important contributions were made to the program by the Cessna Aircraft Company, which participated as a subcontractor. Under the direction of D. J. Ahrens and W. B. Bloedel, the Cessna Aircraft Company provided valuable data with regard to general aviation structure, designs, and procedures and develed a computer program for selecting accident data from NTSB tapes. M.A. Gamon, W.L. LaBarge and P.C. Durup, of the Lockheed-California Company, participated in the program. The Lockheed effort was performed under the supervision of J.E. Wignot (Dynamic Loads) and R.F. O'Connell (Aeromechanics Department).

SUMMARY

This report contains Volume III of the General Aviation Airplane Structural Crashworthiness User's Manual. General information is presented in this report to assist the general aviation airplane industry designer in developing improved structural crashworthiness designs. This report is initiated for the purpose of providing the General Aviation Manufacturers Association (GAMA) members with the basis for understanding the types of procedures, methods and data that are available with regard to structural crashworthiness. This document contains the following sections:

1. General Aviation Airplane Operational and Structural Characteristics
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3. Occupant Injury Assessment
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Each section has its own numbering and reference system, thus, it can be readily updated to include revised or additional information, as such data becomes available. The information presented in this Volume is intended to compliment the KRASH User's Manual (Volume 1) as well as other analytical or test methods that are applicable to structural crashworthiness design.

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INTRODUCTION

Recent advances in the state-of-the-art of analytically modeling vehicles provides the potential for assessing and improving crashworthiness capability during the initial stages, wherein it is most economical to do so. In the past, emphasis has been placed on developing improved crashworthy designs based on test results. While both test and analytical techniques can provide significant contributions to facilitate the design of improved general aviation airplanes insofar as structural crashworthiness is involved, designers will also benefit from information pertinent to related areas. Included in these related areas are occupant injury assessment, type and availability of structural data, methods of assessing crashworthiness, general aviation airplane operating characteristics and the crash environment. The intent of this document is to initiate for the general aviation airplane designers a structural crashworthiness document which complements the KRASH User's Manual in that it contains general information pertinent to crashworthiness design. In some respects this document is similiar to the U.S. Army Crash Survival Design Guide. However, at present it is more limited in scope. Where applicable, data contained in the U.S. Army Crash Survival Design Guide is incorporated. At present this document is oriented toward applications, procedures, techniques and structural data appropriate for structural analysis of light fixed-wing aircraft. No attempt is made to include such subjects as fuel systems, seat and restraint systems design criteria, emergency escape provisions and post crash fire design criteria. While these subjects are important aspects for the safety of occupants, detailed treatment of each of these areas can be extensive and is beyond the scope of this document, at the present time. It is anticipated that future participation by general aviation industry members will help expand this document.

This document is formulated in such a manner that it can be readily updated in the following manner:

1. New sections pertaining to related subject matter can be added.

2. Existing sections can be revised or expanded since they are independent of one another and contain their own numbering system and references.

SECTION 1

GENERAL AVIATION AIRPLANE OPERATIONAL AND STRUCTURAL CHARACTERISTICS

1.1 INTRODUCTION

The occupant's chances to escape serious or fatal injuries depend on the the crash environment, the occupant restraint system, the manner in which the structure surrounding the habitable space deforms and the forces that are imposed on the occupant from the response of the airplane and/or the occupant's motion relative to hardware. An airplane's structural characteristics have a potentially strong influence on the occupant's chances for survival during a crash. Since the loads imposed on the airframe and the occupants are a function of airplane usage, structural design, location of major masses and attachments, the identification of the various airplane configurations and associated characteristics will assist in the formulation of mathematical models and supporting guidelines. The purpose of this section is to provide a general description of the different airplane configurations and the types of structure which have to be modeled. Airplane usage, operational characteristics, and structural characteristics are defined and airplane categories are presented.

1.2 AIRPLANE USAGE

The results of a survey describing the operating characteristics for light fixed-wing general aviation airplanes currently flying and/or in production by major domestic manufacturers are described in Reference 1. Included in this survey are 61 airplane models which are classified into the following four configurations:

- Single-engine, low-wing

- Single-engine, high-wing
- Twin-engine, low-wing
- Twin-engine, high-wing

Of the 61 airplane models surveyed (Reference 1), the breakdown by configuration is:

- (24) single-engine, low-wing
- (20) twin-engine, low-wing
- (13) single-engine, high-wing
- (4) twin-engine, high-wing

In addition, the following usage categories are established:

a. Agriculture: Application of chemicals or seeding crops.

b. Aerobatic, sport: Performance of sporting and aerobatic functions.

c. Training: Used for instructional purposes, usually meaning initial flight training. Some of the larger aircraft may be classified as a trainer for instrument rating purposes.

d. Business, executive: This category may overlap into several areas. Applies to airplanes used in the performance of business functions.

e. Commuter, transport, air taxi: Carrying of people for commercial use, such as an airline service.

f. Cargo, freight: Hauling of freight or cargo.

g. Utility: This is a multi-purpose usage. Generally, an airplane in this category is used to perform business commuter, and/or cargo carrying functions.

h. Pleasure: Generally applicable to smaller economical airplanes. Usually encompasses sport and training flying.

Most of the airplanes, with the exception of the agriculture airplane, have multiple uses. Table 1-1 shows the evaluation regarding the usage for the 61 airplane models surveyed.

TABLE 1-1. GENERAL AVIATION AIRPLANE USAGE			
Twin-Engine Airplanes		**Single-Engine Airplanes**	
Executive/business	(18)	Executive/business	(20)
Commuter	(10)	Aerobatic, sport (a)	(11)
Cargo-freight	(5)	Training (a)	(11)
Training	(3)	Commuter	(10)
Utility	(2)	Utility	(7)
		Agricultural	(5)
		Cargo/freight	(4)

(a) Most sport, training and aerobatic airplanes are used for pleasure flying

A matrix of airplane maximum takeoff weight, airplane configuration and usage is presented in Table 1-2.

1.3 AIRPLANE OPERATIONAL CHARACTERISTICS

Light fixed-wing general aviation airplanes have maximum takeoff weight, stall and cruise speed characteristics as shown in Table 1-3. Included in Table 1-3 are the usage and accommodations associated with each type of configuration.

1.4 AIRPLANE CATEGORIES

To facilitate the development of improved structural crashworthiness for a vehicle it is important to recognize those factors that influence the occupant's chances to survive a severe crash. The crash environment depends to a large extent on the type of flying that is being performed as well as the capability of the airplane to perform certain missions. The latter, in turn, dictates the weight of the airplane, which combined with the velocities associated with a crash condition determine the amount of energy that has to be absorbed by the ground and structure at impact. How well the structure absorbs the energy depends on the location of the occupant and the manner in which the occupant is supported, the structural strength and load

TABLE 1-2. MATRIX OF AIRPLANE CONFIGURATIONS AND MAXIMUM TAKEOFF WEIGHT AND USAGE

Maximum Takeoff Weight (lb)	Single-Engine Low-Wing	Single-Engine High-Wing	Twin-Engine Low-Wing	Twin-Engine High-Wing
≤ 2000	Trainer Utility	Aerobatic Pleasure Trainer		
2000-2499	Trainer Sport Utility Pleasure	Trainer Business Aerobatic Utility Pleasure		
2500-3999	Business Agriculture Commuter Trainer Utility Pleasure	Business Utility Cargo/Freight Commuter Pleasure		
4000-5999	Agricultural (a)		Business Commuter Cargo	Business Commuter
6000-7999			Business Commuter Cargo/Freight	Business Commuter Cargo/Freight
8000-12500				Business Commuter

(a) Consits of one low-wing and one biplane

TABLE 1-3. RELATIONSHIP OF GENERAL AVIATION AIRPLANE CONFIGURATIONS TO PERFORMANCE PARAMETERS, USAGE AND OCCUPANT CAPACITY

Airplane Configuration	Maximum Takeoff Weight (Pounds)	Stall Speed Range, Flap Down (Knots)	Cruise Speed Range, 75 Percent Max. Power (Knots)	Primary Usage	Occupant Capacity
Single-Engine Low-Wing	< 2500	49-54	108-128	Training **Pleasure**	1-4
Single-Engine High-Wing	< 2500	38-45	100-114	Training **Pleasure** Aerobatics	2-4
Single-Engine Low-Wing	2500-4000	49-61	132-176	Business Commuting Training Utility	4-7
Single-Engine High-Wing	2500-4000	45-59	124-163	Business Utility Cargo	4-7
Single-Engine Low-Wing (a)	2900-6000	47-59	101-138	Agriculture	1
Twin-Engine Low-Wing	3700-10900	59-82	162-247	Commuting Business Cargo Commuting	4-17 (b)
Twin-Engine High-Wing	4600-10250	61-77	170-280	Business Cargo Commuting	4-11

(a) Includes one biplane

(b) 17 occupants for 1 airplane only, otherwise maximum is 11

deformation characteristics, the location of major masses relative to the impact point and to the occupant, the techniques used in attaching structure and the direction in which the impact forces act. Consequently, it can be seen that occupant survivability, as a minimum, is a function of such factors as:

- Structural configuration (high-wing, low-wing, single-engine, twin-engine)
- Operating speeds (stall and cruise)
- Usage (mission requirements)
- Maximum takeoff weight
- Accommodations (number and location of occupants)

In Reference 1 these factors were evaluated and several categories were established for light fixed-wing general aviation airplanes. The use of these categories is considered essential to the development of meaningful crash design criteria. The categories are described in Table 1-4. Figure 1-1 shows the range of weight (maximum takeoff) and operating speed (stall and cruise) associated with the various airplanes. Also shown in Figure 1-1 is the region wherein the airplane categories are located.

1.5 STRUCTURAL CHARACTERISTICS

Table 1-5 identifies the structural design characteristics of the major structure regions such as the wing, fuselage, engine attachments, landing gear and tail unit associated with different categories of airplanes. While airplanes can differ substantially in detail design, the information in Table 1-5 indicates that there are basically two types of design concepts for each of the structural items that need to be modeled in crash analyses. For example, the engine mounts are generally either of a steel tube arrangement type or of a keel type.

TABLE 1-4. CATEGORIES FOR GENERAL AVIATION AIRPLANES

Category	Airplane Configuration	Maximum Takeoff Weight (Pounds)	Stall Speed Range, Flap Down (Knots)	Cruise Speed Range, 75 Percent Max. Power (Knots)	Primary Usage	Occupant Capacity
1	Single-Engine A. Low-Wing B. High-Wing	<2500	38-54	100-128	Training Sport Aerobatic Pleasure	1-4
2	Single-Engine A. Low-Wing B. High-Wing	2500-4000	45-61	124-176	Business Utility Commuting Training	4-7
3	(a) Single-Engine Low-Wing	2900-6000	50-53	101-122	Agriculture	1
4	Twin-Engine A. Low-Wing B. High-Wing	>4000-10900	59-82	162-280	Business Cargo Commuting	4-11 (b)

(a) Includes one biplane

(b) Except for 1 airplane accommodates 17

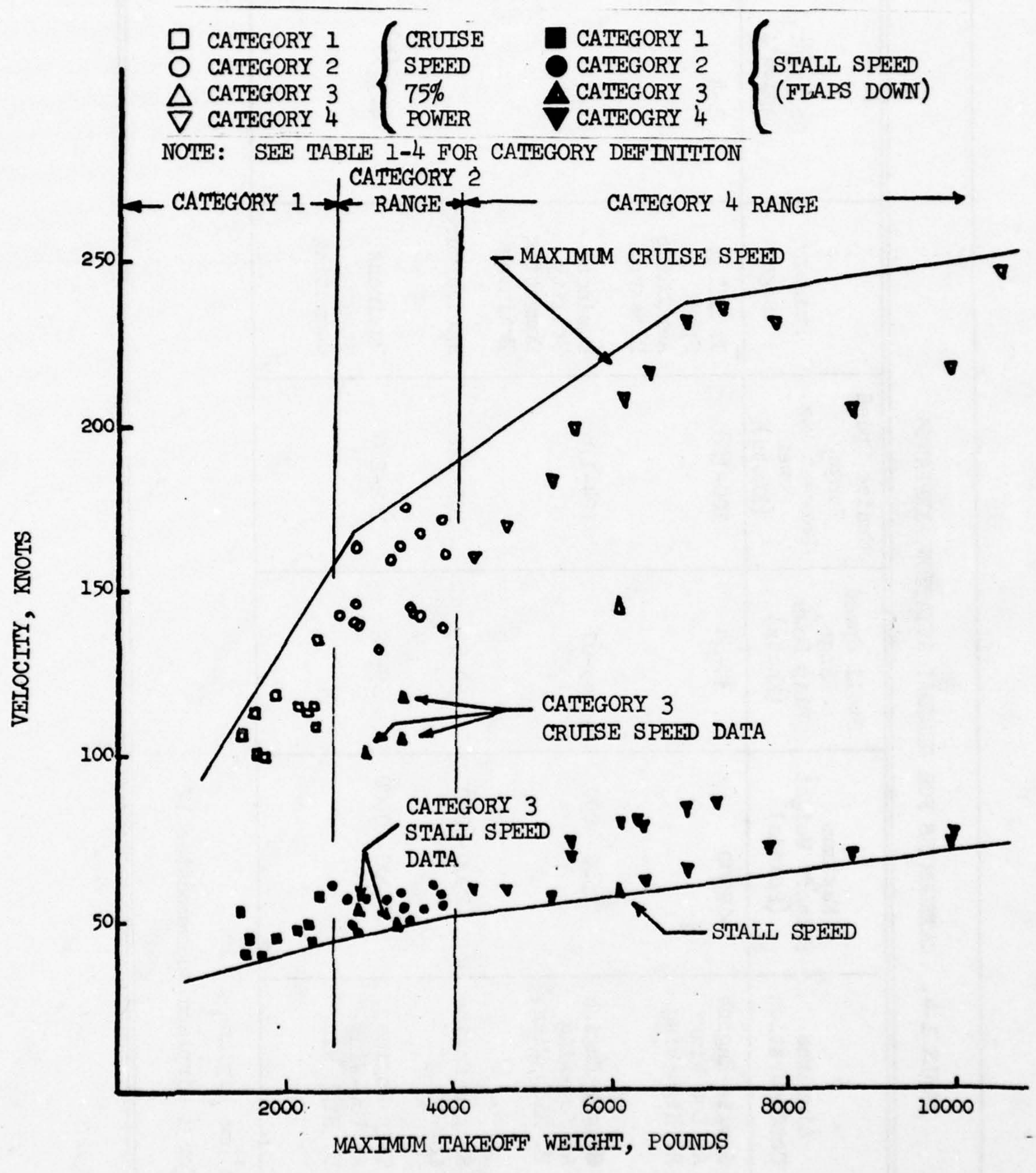

Figure 1-1. Operational Velocity/Weight Envelope for Current General Aviation Airplanes

TABLE 1-5. STRUCTURAL DESIGN CHARACTERISTICS OF CURRENT GENERAL AVIATION AIRPLANES

Structure	Category 1 Single-Engine, Low or High-Wing, Weight < 2500 lb.	Category 2 Single-Engine, Low or High-Wing, Weight 2500-4000 lb.	Category 3, Single-Engine, Low-Wing, (a) Agricultural Use Only, Weight 2500-4000 lb.	Category 4 Twin-Engine, Low or High-Wing, Weight 4000-10900 lb.
Wing	o Braced Wing 1,2 or 3 spar, mostly metal, some wood spars o Cantilever 1,2 or 3 spar, mostly metal, some wood spars	o Cantilever 1,2 or 3 spar mostly metal, some wood spars	o Braced 1 or 2 spar metal construction	o Cantilever 1,2 or 3 spar, mostly metal, some wood spars o One braced, all metal
Fuselage	o All-metal semi-monocoque o Rectangular section welded steel tube o Keel formed by floor and lower skin (cabin), semi-monocoque (rear)	o All-metal semi-monocoque o Weld steel tube o Welded steel tube (cabin), semi-monocoque (rear)	o Rectangular section welded steel tube o Welded steel tube (cabin), semi-monocoque (rear) o Long nose section o Isolated occupant region o Strong turnover structure	o All-metal semi-monocoque
Engine Attachment	o Tubular	o Tubular o Keel	o Tubular	o Tubular o Keel
Landing Gear	o Tail wheel o Tricycle o Cantilever spring main gears o Nonretractable	o Tail wheel retractable o Tricycle retractable and nonretractable o Cantilever spring main gears o Hydraulically activated system	o Tail wheel type o Nonretractable o Cantilever spring main gears	o Mostly tricycle retractable o Some nonretractable with cantilever spring main gears o Hydraulic or electromechanical actuated system
Tail Unit	o Cantilever all-metal o Welded steel tube and channel with fabric covering	o Cantilever all-metal	o Welded steel tube o Cantilever all-metal	o Cantilever all metal

(a) With the exception of one biplane

The wing is generally of a cantilever design with either a one, two, or three spar arrangement. The lighter weight airplanes usually have supporting brace struts for the wing. While most airplane structure is all-metal, some of the lighter weight airplanes use wood spars. The wings for the heavier airplanes, particularly the twin engine airplanes (4000 pounds), generally are unbraced and of an all-metal construction. The tail structure for most airplanes is usually an all-metal cantilever structure. The landing gear arrangement tends to be a function of weight, the light weight (<2500 pounds) airplanes use a tricycle or tailwheel nonretractable landing gear, wherein the main gears are cantilevered metal springs. The agricultural airplanes use tailwheel type nonretractable landing gears. The heavier single-engine airplanes (2500-4000 pounds) predominantly utilize retractable tricycle gears. Nearly all the twin engine airplanes have retractable tricycle gear designs.

Fuselage sections for most airplanes, with the exception of agricultural airplanes, are of semi-monocoque construction. Some of the single-engine airplanes and all of the agricultural type airplanes use a welded steel tube construction for the cabin region. In some instances a combination of semi-monocoque and welded tube construction is employed. The agricultural airplanes generally contain design features unique only to their types; such as, isolated occupant region, long nose section and strong turnover structure. Occupant accommodations, designs, and arrangements vary widely and include individual seats, reclining seats, front and rear facing seats, bench seats, side by side seating, tandem seating, articulated seats, progressively collapsible seats, lap belt and shoulder harnesses.

The details associated with the structures that are used in the design of general aviation airplanes can differ substantially. In addition, the analytical techniques that are available to model structure vary widely in their requirements with regard to describing and treating structural behavior. Consequently, a comprehensive discussion encompassing all types and configurations is impractical. However, it is important to recognize that the salient characteristics of structures that need to be represented include failure load, failure mode energy absorption and deformation.

The ability to properly represent these items, regardless of which analytical technique is used, will facilitate the development of improved structural crashworthiness via analytical modeling. For example, as noted earlier in this section, engine mounts are generally either a tubular arrangement or a keel arrangement. Figure 1-2 illustrates one such arrangement for each of these two types. The structural characteristics for these two arrangements will differ and consequently the modeling requirements will have to satisfactorily represent their behavior if a reasonably accurate assessment of occupant survivability is to be performed. The failure of the tubular structure (Figure 1-2 (a)) may likely be through dynamic instability which will occur at a load which is substantially below the yield stress. Where failure through elastic instability occurs the load carrying capability of the structural element tends to decrease rapidly as deflection increases once the failure load has been reached. This type of failure will result in little energy being absorbed. A math model to describe this behavior should be able to account for the critical buckling load, the deflection at which buckling occurs and the characteristics of load versus deflection in the post failure region.

The keel mount arrangement shown in Figure 1-2 (b) can be expected to behave differently than the tubular mount arrangement. The mount structure for this situation is more an integral part of the fuselage. The deformation of this structure will involve more crushing of structure and as such the load-stroke curve can be expected to show more plastic deformation in the post-failure region. The failure behavior of this structure, as well as the structure to which it attaches, are to be described if an analytical approach is to be successful. The accuracy of predicting structural behavior depends entirely on the validity of data that is available as well as the accuracy that is required for the intended purpose of using the results. Detail design considerations may require finite representations of critical regions. On the other hand, preliminary designs may benefit from a description of an aircraft's gross behavior during a crash since the data that is being used is also gross in the sense that only concepts and sizing are available at the time of the analysis.

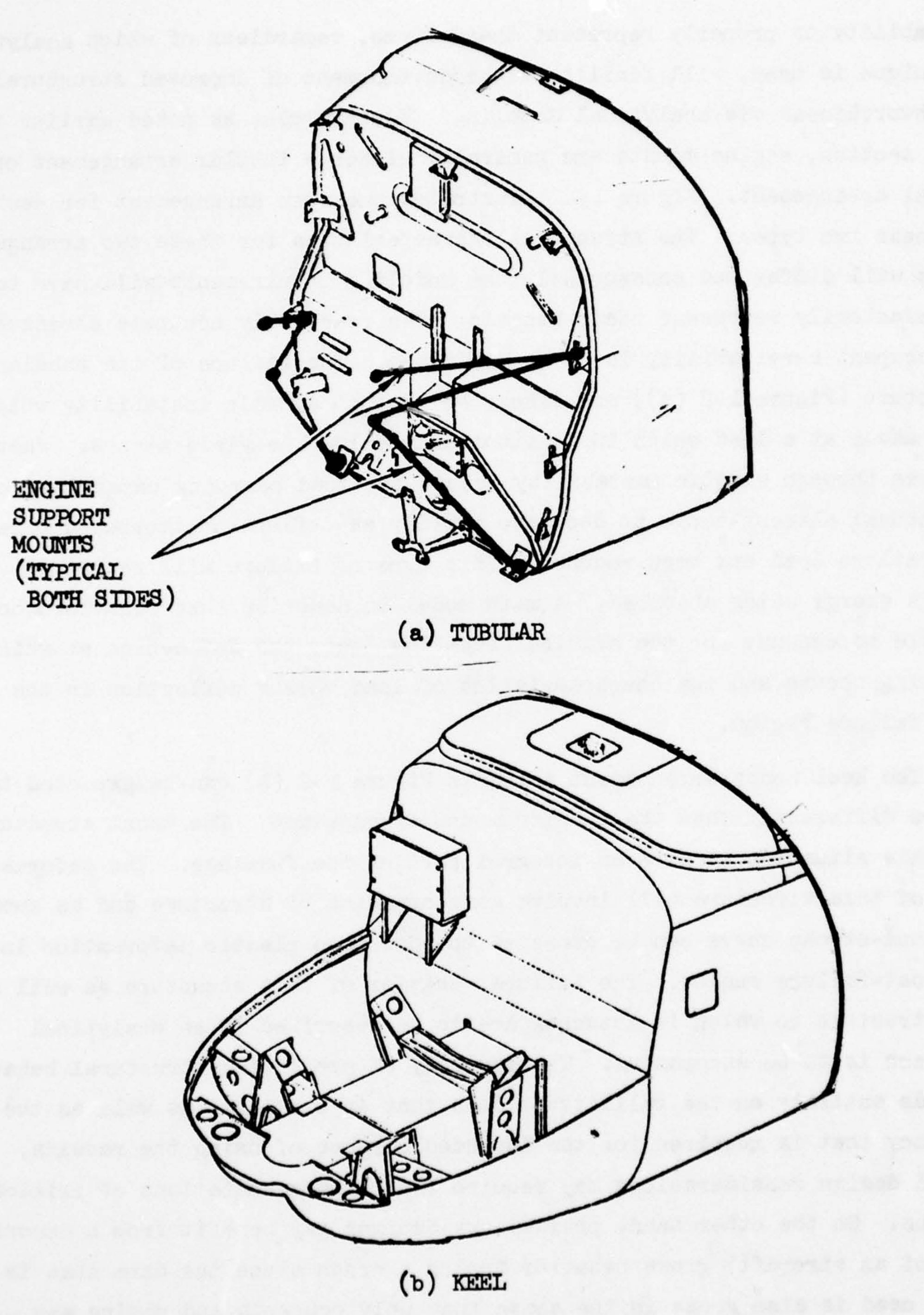

Figure 1-2. Two Typical Engine Mount Arrangements

1.6 REFERENCES

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SECTION 2

CRASH ENVIRONMENT

2.1 INTRODUCTION

The purpose of this section is to provide data which is pertinent to describing the crash environment for light fixed-wing general aviation airplanes. Since the airplanes vary widely with regard to mission requirements, operational speeds, operating weights, accommodations, and structural configuration it is important that the description of the crash environment take these factors into consideration. Ideally it is desirable to have the occupants survive for all accident conditions, including those that occur at maximum operating speeds. However, from a practical viewpoint it may not be possible to achieve such a high-velocity-impact capability, without unduly penalizing the vehicle with added weight. Therefore, it is important that the structure be designed to specified accident levels which have not only a high probability of occurring but also have a high potential to cause serious or fatal injuries. Consequently, the discussions in the following subsections describe the different airplane configurations, their operating conditions and probable accident conditions associated with each type.

2.2 AIRPLANE OPERATIONAL SPEEDS

Light fixed-wing general aviation airplanes are designed with operational speeds which are commensurate with their mission requirements and operating weights. Table 1-3 and Figure 1-1 show the range of stall and cruise speeds associated with airplane configuration, takeoff weight, and usage.

2.3 AIRPLANE CATEGORIES

There are several significant factors associated with airplane design and use which have an influence on the occupant's chances for survival during a crash. These factors are discussed in Section 1.0. Different airplane categories have been established [1], as are shown in Table 1-4. Since not all airplanes can be expected to be exposed to the same crash environment, the separation by category provides an opportunity to develop improved crashworthiness designs in a meaningful and effective manner. Figure 1-1 shows the range of weights (maximum takeoff) and operating speeds (cruise and stall) which are related to current general aviation airplanes. The relationship of the different categories to these parameters is also noted. In addition the boundary of cruise and stall speed are shown with solid lines. The crash environment representative of probable accident conditions for the different airplane categories falls somewhere between these two lines.

2.4 ACCIDENT DATA

Accident data for light fixed-wing airplanes is compiled principally by the National Transportation Safety Board (NTSB) in Washington D.C. and by the FAA Civil Aeromedical Institute (CAMI) in Oklahoma City. CAMI data generally covers only a selected number of accidents that occur mostly in the states of Oklahoma, Texas and Kansas. In addition to these two primary sources of accident data, some individual states compile accident records. Pertinent studies have been performed using NTSB, CAMI, and/or other available accident records and are reported in References (1) through (5).

2.4.1 CAMI Data

Selected crashworthiness data from CAMI investigations of general aviation accidents are available in published form (References 1 and 2). The CAMI accident records contain the following data, if available:

- o Airplane make and model

- Type of conditions under which an accident occurred (i.e. agricultural mission, stall on turn, faulty engine, obstacle impact)
- Impact angle
- Post crash behavior
- Stopping distance
- Structural damage including approximate cabin volume distortion
- Use and failure of seat belts and harnesses
- Number of occupants involved
- Occupant injuries and/or fatalities
- Cause of injuries/fatalities

In Reference 7, a review and evaluation of 18 CAMI accident cases was performed and the results are presented in Table 2-1. The data shows the distribution of accidents by:

- Phase of operation
- Type of accident
- Angle of impact
- Presence of roll/yaw

and the frequency of occurrence and/or degree of:

- Cabin damage
- Structure damage
- Impact with controls
- Seat failures
- Injuries
- Lap belt failures

Although limited to 18 accidents, the results are consistent with results obtained from much broader surveys (1, 2, 4 and 5). Unfortunately, accident records rarely provide quantitative data, other than the angle

TABLE 2-1 RESULTS OF SELECTED CAMI ACCIDENT DATA (REFERENCE 7)

Frequency of Occurrence		Damage, Failures, Injuries	
Phase of Operation		**Cabin Damage**	
Takeoff	4	Intact, None	4
Landing (a)	4	Minor, Moderate	8
Cruise (a)	8	Substantial, Destroyed	6
Aerial Application	2		
		Structure Damage	
Type of Accident		Intact, None	0
Stall	3	Minor, Moderate	7
Ground/Water Impact	5	Substantial, Destroyed	11
Contact w/tree/object	5		
Landing Short	1	**Impact with Control Panel/Knobs**	
Side of Hill	2	Yes	15
Miscellaneous	2	No	1
		Unknown	2
Angle of Impact (degrees)			
0-10	4	**Seat Failures**	
11-20	5	Yes	9
21-30	1	No	3
31-45	3	Unknown	6
46-90	4		
Unknown	1	**Injuries** (Total)	
		Fatalities	15
Roll/Yaw Attitude		Serious and/or Critical	15
Significant Roll/Yaw	3	Moderate	6
Slight or No Roll/Yaw	9	Minor, None	4
Overturn	2		
Unknown	4	**Lap Belt Failures** (TOTAL)	
		Yes	6
Terrain		No	27
Hard Soil	7	Unknown	7
Grassy Land	4		
Water	1		
Mud/Swamp	2		
Trees	1		
Mountainous/hilly	2		
Unknown	1		

(a) Generally impact occurs with tree, object, or ground, due to bad weather or stall.

of impact, which can be related to the impact condition such as velocities, altitudes, and roll rates. It is important to note from the data in Table 2-1 that in 13 of the 17 cases (77.7%), wherein data is available, the impact angle is 45 degrees or less.

2.4.2 NTSB Data

NTSB accident records encompass a much larger number and wider range of accidents than do the CAMI investigations. This data is available on tape by calendar year. An aircraft accident analysis request form for using NTSB data includes the following items:

- o Airplane and accident identifying and general information (location, make, model, phase of operation)
- o Emergency conditions (weather data, airport information)
- o Flight itinerary (departure, enroute, destination)
- o Accident site/pilot data (terrain, pilot statistics)
- o Cause/factor
- o Medical factor
- o Injuries (pilot, copilot, crew, passengers)
- o Remarks, cause
- o Engine-propeller failure data
- o Weather at the accident site
- o Flight crew data
- o Human factors information
- o Fire information
- o Administrative data
- o Aerial application data (applicable to agricultural airplanes only)
- o Collision between aircraft information
- o Ditching survival information

The amount of information potentially available is large. However, the nature of crash accident investigation reports, which are usually an after-the-fact gathering of data, rarely results in a complete set of data being available in an accident record. Furthermore, much of the data contained in the NTSB data tape is pertinent to other than structural crashworthiness considerations (e.g. fire hazards, biomechanics, engine failure data). As part of the effort described in Reference 7 a digital computer program* was developed which searches and obtains selected data from the NTSB tapes which are applicable to the development of a crash environment design criteria. Details of this program including a description, sample problem and listing are provided in Reference 7. Briefly stated the accident data program provides the following:

- A printout of the available data from the accident reports for a particular airplane including date, aircraft make, model and damage, kind of flying, type of accident, phase of operation, cause/factor injury index, qualitative assessments of impact severity, rate of deceleration, damage severity, and data regarding stopping distance, direction of principal deceleration, seat belt failures and death due to fires, if available. A sample printout of a modified accident report, obtained from NTSB tapes, is shown in Figure 2-1.

- A summary of accident data by airplane model for each year. Derivatives of a model are combined (i.e. Cessna Model 150 includes 150, A150, A150K, etc.). Included in the summary are airplane manufacturer and model designations, year, general information (number of accidents and occupants involved, number of accidents with fatalities and injuries), totals of injuries, flight conditions, and accident types, inpact conditions, aircraft cabin accommodations and impact area (terrain).

- A summary of accident data for all airplanes for a given year or period of years. The format of the data for this summary is the same as for the individual airplane summary. A sample of this output is shown in Figure 2-2.

The NTSB accident summary for 1971-73 included a survey of accidents. All 8,491 accidents were surveyed. Of this total, 8,030 (95%)** involved airplane models that were used to establish the different airplane categories presented in Table 2-4. The data was reviewed with regard to the potential for an occupant fatality to occur (for accidents in which at least one injury), the distribution of accidents by terrain conditions, the total number of occupants involved, the total number of fatalities and the total

* The program was developed by the Cessna Aircraft Company.
** 461 foreign manufactured airplanes marketed or assembled by domestic firms are not included.

```
CATE . . . . . . . . . . . . . . . . . . . . . . . .   04/22/72
AIRCRAFT MAKE . . . . . . . . . . . . . . . . . . . .   AERO COMDR
AIRCRAFT MCCEL  . . . . . . . . . . . . . . . . . . .   500-B

AIRCRAFT CAMAGE . . . . . . . . . . . . . . . . . . .   DESTRCYED
FIRE AFTER IMPACT . . . . . . . . . . . . . . . . . .   YES
KIND OF FLYING (GENERAL AVIATION) . . . . . . . . .   PLEASURE/PERSONAL TRANSP

TYPE OF ACCICENT, FIRST . . . . . . . . . . . . . .   CCLLIDED WITH
TYPE OF ACCICENT, FIRST . . . . . . . . . . . . . .   TREES

PHASE OF OPERATICN, FIRST . . . . . . . . . . . . .   LANDING
PHASE OF OPERATION, FIRST . . . . . . . . . . . . .   FINAL APPROACH
AIRPORT PRCXIMITY . . . . . . . . . . . . . . . . .   WITHIN 5 MILES
RUNWAY COMPCSITION  . . . . . . . . . . . . . . . .   CONCRETE
RUNWAY LENGTH . . . . . . . . . . . . . . . . . . .   10000
TERRAIN (TYPE) OF AIRPORT . . . . . . . . . . . . .   HILLY

                 CAUSE / FACTOR
CAUSE / FACTOR  . . . . . . . . . . . . . . . . . .   IMPRCPER IFR OPERATION
CAUSE / FACTOR  . . . . . . . . . . . . . . . . . .   ATTEMPTED OPERATION W/KNOWN DEFICIENCIES IN EQUIPMENT
CAUSE / FACTOR  . . . . . . . . . . . . . . . . . .   LACK CF FAMILIARITY WITH AIRCRAFT
CAUSE / FACTOR  . . . . . . . . . . . . . . . . . .   LOW CEILING
CAUSE / FACTOR  . . . . . . . . . . . . . . . . . .   RAIN
CAUSE / FACTOR  . . . . . . . . . . . . . . . . . .   FOG

                 INJURY - INDEX
                                                         F  S  M  N  Z  T
PILOT . . . . . . . . . . . . . . . . . . . . . . .     1              1
PASSENGERS  . . . . . . . . . . . . . . . . . . . .     4              4
TCTAL ABOARD  . . . . . . . . . . . . . . . . . . .     5              5

REMARKS . . . . . . . . . . . . . . . . . . . . . .     ACFT RADIOS OPERATED INTERMITTENTLY WHILE ENROUT
                                                        E. DESCENDED BLO MDA ON ILS APCH.1 HR DUAL IN TYPE
AIRCRAFT SERIAL NUMBER  . . . . . . . . . . . . . .   00001384-138
RATE OF CECELERATION  . . . . . . . . . . . . . . .   EXCESSIVE
DIRECTION CF PRINCIPLE DECELERATION . . . . . . . .   FORWARD
STOPPING DISTANCE . . . . . . . . . . . . . . . . .     85
CAMAGE SEVERITY - IMPACT (NCN-TRANS. AIRCRAFT)        EXTREME
```

Figure 2-1. Individual Airplane Output Format, NTSB Data

GRAND TOTAL ACCIDENT SUMMARY FOR 1971 through 1973

AIRCRAFT MANUFACTURER / MODEL - ALL / ALL

MAXIMUM TO WEIGHT - POUNDS

WING CONFIGURATION

NUMBER OF ENGINES / LOCATION -

GENERAL INFORMATION

TOTAL NUMBER OF ACCIDENTS SURVEYED - - - - - - - - - - - - - - -	8491
TOTAL APPLICABLE ACCIDENTS SURVEYED - - - - - - - - - - - - - - -	7471
TOTAL NUMBER OF OCCUPANTS - - - - - - - - - - - - - - - - - - -	15609
AVERAGE NUMBER OF OCCUPANTS PER ACCIDENT - - - - - - - - - -	2
NUMBER OF ACCIDENTS WITH AT LEAST ONE (1) FATAL INJURY - -	1217
NUMBER OF ACCIDENTS WITH AT LEAST ONE (1) SERIOUS INJURY - AND NONE MORE SERIOUS	638
NUMBER OF ACCIDENTS WITH AT LEAST ONE (1) MINOR INJURY - - AND NONE MORE SERIOUS	1032
NUMBER OF ACCIDENTS WITH NO INJURY - - - - - - - - - - - - - - AND NONE MORE SERIOUS	4589

***** TOTALS OF SERIOUSNESS OF INJURIES *****

	FATAL	SERIOUS	MINOR	NONE
PILOT	1134	584	956	4795
COPILOT	81	21	15	91
PASSENGERS	1257	544	897	4767
* OTHER	48	40	47	310

* OTHER INCLUDES DUAL STUDENT & CHECK PILOT

Figure 2-2. Grand Total Accident Summary For 1971 through 1973

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FLIGHT CONDITIONS -

TOTAL NUMBER OF ACCIDENTS WHICH OCCURRED DURING THE FOLLOWING FIVE MAJOR PHASES OF OPERATION / NUMBER OF ACCIDENTS WITH AT LEAST ONE FATALITY WHICH OCCURRED DURING THE MAJOR PHASE

TAKEOFF - - 1355 / 113

IN FLIGHT - 2450 / 888

LANDING - - 3666 / 216

OTHER - - - 375 / 16

NOT REPORTED 11 / 6

NINE (9) MOST FREQUENT MINOR PHASES OF OPERATION WITHIN THE FIRST THREE MAJOR PHASES ABOVE LISTED IN DESCENDING ORDER OF FREQUENCY

MINOR PHASE OF OPERATION	TOTAL NO. OF ACCIDENTS	********* INJURIES ********* FATAL	SERIOUS	MINOR	NONE
1. NORMAL CRUISE	477	411	200	366	186
2. INITIAL CLIMB	383	231	193	354	152
3. FINAL APPROACH	252	125	148	221	62
4. UNCONTROLLED DESCENT	249	511	25	14	1
5. LEVEL OFF/TOUCHDOWN	201	27	69	237	143
6. ROLL	106	3	16	120	45
7. TRAFFIC PATTERN-CIRCLING	101	67	59	71	30
8. GO-AROUND	98	46	52	84	24
9. OTHERS	590	503	269	309	115

EIGHT (8) MOST FREQUENT TYPES OF ACCIDENTS WITHIN THE FIRST THREE MAJOR PHASES ABOVE LISTED IN DESCENDING ORDER OF FREQUENCY

TYPE OF ACCIDENT	TOTAL NO. OF ACCIDENTS	********* INJURIES ********* FATAL	SERIOUS	MINOR	NONE
1. ENGINE FAILURE OR MALFUNCTION	719	289	318	743	300
2. COLLISION WITH GROUND/WATER	569	961	180	129	44
3. COLLIDED WITH	549	480	255	309	118
4. STALL	540	550	271	256	94
5. GROUND-WATER LOOP-SWERVE	119	1	23	141	43
6. OVERSHOOT	99	19	40	114	76
7. OTHERS	285	228	104	224	115
8. NOT REPORTED					

NOTE -- OTHER IS SUM OF ALL ACCEPTABLE PHASES AND TYPES EXCEPT THOSE LISTED

Figure 2-2. (Continued)

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IMPACT CONDITIONS

TOTAL NUMBER OF ACCIDENTS WHICH RECORD IMPACT ANGLES - 27

IMPACT ANGLE NUMERICAL SUMMARY -

AVERAGE ANGLE DEGREES	IMPACT ANGLE CATEGORIES - DEGREES						
	0 -15	16-30	31-45	46-60	61-75	76-90	90+
62	4	2	5	1	2	13	

TOTAL NUMBER OF ACCIDENTS WHICH RECORD IMPACT VELOCITY - 2

IMPACT VELOCITY NUMERICAL SUMMARY -

AVERAGE VELOCITY KNOTS	IMPACT VELOCITY CATEGORIES - KNOTS				
	1-30	31-60	61-90	91-120	120+
148			1		1

TOTAL NUMBER OF ACCIDENTS WHICH RECORD STOPPING DISTANCES - 499

STOPPING DISTANCE NUMERICAL SUMMARY -

AVERAGE STOPPING DISTANCE - FEET	STOPPING DISTANCE CATEGORIES - FEET						
	1 -60	61-120	121-180	181-240	241-300	301-360	360+
194	174	87	73	48	38	17	62

OCCUPANT INJURY NUMERICAL SUMMARY AT RESPECTIVE AIRCRAFT DAMAGE SEVERITY INDICES -

DAMAGE SEVERITY	* * * * FATAL	OCCUPANT SERIOUS	INJURY MINOR	* * * * NONE
EXTREME	1701	152	18	1
SEVERE	96	59	14	4
MODERATE	21	6	3	2
MINOR	17	1	4	
NONE				5

Figure 2-2. (Continued)

AIRCRAFT CABIN ACCOMMODATIONS -

NUMBER OF ACCIDENTS IN WHICH SEAT FAILURE OCCURRED	149	
TOTAL NUMBER OF SEAT FAILURES	328	
NUMBER OF ACCIDENTS IN WHICH SEAT BELT FAILURE OCCURRED	204	
TOTAL NUMBER OF SEAT BELT FAILURES	344	
* NUMBER OF SHOULDER HARNESS USED	237	
* NUMBER OF SHOULDER HARNESS FAILURES	21	
* NUMBER OF CRASH HELMETS USED / NOT USED	442 /	68

* APPLICABLE TO AGRICULTURAL AIRCRAFT ONLY

IMPACT AREA

PERCENT OF ACCIDENTS WHICH OCCURRED IN PARTICULAR TERRAIN TYPE

TERRAIN TYPE	PERCENT ACCIDENT OCCURRENCE (1)
UNKNOWN/NOT REPORTED	52
LEVEL,FLAT	19
ROLLING	8
MOUNTAINOUS	6
DENSE WITH TREES	4
HILLY	4
WATER-LAKES,RIVERS,ETC.	3
PLOWED	2
OTHER	1
CITY AREA	1

(1) PERCENT IS RATIO OF PARTICULAR TERRAIN TO NUMBER OF ACCIDENTS SCREENED

Figure 2-2. (Continued)

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CAUSE / FACTOR GRAND SUMMARY

CAUSE / FACTOR SUMMARY

CAUSE	FATAL ACCIDENTS	NONFATAL ACCIDENTS
* * PILOT * *		
1. INADEQUATE PREFLIGHT PREPARATION AND/OR PLANNING	200	829
2. FAILED TO OBTAIN/MAINTAIN FLYING SPEED	304	630
3. FAILED TO MAINTAIN DIRECTIONAL CONTROL	3	740
4. IMPROPER LEVEL OFF	4	687
* * COPILOT * *		
1. IMPROPER LEVEL OFF		5
2. IMPROPER LEVEL OFF		4
* * DUAL STUDENT * *		
1. IMPROPER LEVEL OFF	8	25
2. IMPROPER LEVEL OFF		32
* * CHECK PILOT * *		
1. IMPROPER LEVEL OFF		7
2. IMPROPER LEVEL OFF		1
* * AIRFRAME * *		
1. BRAKING SYSTEM (NORMAL SYSTEM)		65
2. NORMAL RETRACTION/EXTENSION ASSEMBLY		59
* * MISCELLANEOUS ACTS, CONDITIONS * *		
1. OVERLOAD FAILURE	52	1067
2. FUEL EXHAUSTION	27	370
3. FUEL STARVATION	24	264
4. MATERIAL FAILURE	13	262

Figure 2-2. (Continued)

number of accidents. To facilitate the evaluation two ratios were established. The first ratio (Ratio(No.1)is for all phases of operation and accident types and relates the total number of fatalities to total number of occupants involved in all of the accidents surveyed. This ratio is defined below as:

$$\text{Ratio (No. 1)} = \frac{\text{total number of fatalities}}{\text{total number of occupants}}$$

The second ratio (Ratio(No.2) defines the number of fatalities relative to the number of occupants involved for a particular accident type for those accidents involving an injury. The data is presented for the stall, the collision with ground/water, and the collision with obstacle accident types.

$$\text{Ratio (No. 2)} = \frac{\text{number of fatalities/number of accidents}}{\text{number of occupants/number of accidents}}$$

$$= \text{(number of fatalities/number of occupants) (for a particular accident type)}$$

Obviously, larger airplanes which carry more passengers will have a higher ratio of fatality/accident than the smaller airplanes. In dividing by the number of occupants involved for each particular accident type a more rational manner of comparing different size and weight airplanes on an equal basis can be utilized. Both ratios are intended to give an indication of the potential of fatality for an occupant for each category of airplane as well as for all the airplanes combined.

Table 2-2 presents a summary of the distribution for the terrain conditions in which light fixed-wing airplanes are involved. It is based on a sampling of airplanes for the three categories for which the majority of accident data is available (categories 1, 2 and 4). Although the distribution of accident terrain conditions varies somewhat for the different airplane configurations, the trend is generally consistent in the order of occurrence. Single-engine airplanes have accidents in rolling, mountainous and hilly terrains somewhat more often, percentage-wise, than do the twin-engine airplanes. This undoubtedly is associated with the differences in primary usages.

TABLE 2-2 SUMMARY OF TERRAIN CONFIGURATIONS FOR ACCIDENTS (NTSB DATA 1971 THROUGH 1973) (REFERENCE 7)

	All Airplanes		Single-Engine, High-Wing (a)		Single-Engine Low-Wing (b)		Twin-Engine Low-Wing (c)	
Type Terrain	Number of Accidents	Percent	Number of Accidents	Percent	Number of Accidents	Percent	Number of Accidents	Percent
Level, Flat	1,444	46.0	339	40.9	175	37.0	43	36.1
Rolling	676	21.6	186	22.5	193	26.0	22	18.5
Mountainous	422	13.5	146	17.6	92	19.4	19	16.0
Hilly	253	8.1	91	11.0	53	11.2	13	10.9
Dense with Trees	253	8.1	67	8.0	30	6.4	15	12.6
City	84	2.7	--	--	--	--	7	5.9
	3,132	100.	829	100.	473	100.	119	100.

(a) Based on Category 1B Type Airplanes, 2-4 Occupants, Sport, Trainer, Pleasure, and Business Usage.

(b) Based on Category 2A Type Airplanes, 2-6 Occupants, Sport, Trainer, and Business Usage.

(c) Based on Category 4 Type Airplanes, 4-10 Occupants, Executive, Commuter, and Cargo Usage.

Considering all airplanes, accidents occur on level, flat terrain in approximately 46% of the accidents. Accidents occur in rolling, mountainous or hilly terrain in approximately 43% of the accidents, while trees or city areas are involved in 11% of the accidents.

Table 2-3 provides a summary of the accident data using the different categories of accidents, the accident data pertinent to the models within each of categories and the two ratios described earlier. The data for all the airplanes indicates that ratio (1) = .147 and ratio (2) = .455, .707 and .39 for stall, collision with ground/water and collision with obstacle type accidents, respectively. The more crashworthy airplanes, whether it be due to the structural design or the crash environment, should show lower ratios than the composite of all airplanes. The smaller lighter weight airplanes and agricultural airplanes generally do.

The data presented in Table 2-3 indicates that the most probable accident for the lighter weight airplanes (<2500 pounds) is a stall condition. The heavier weight airplanes (>2500 pounds) experience accidents which occur at higher speeds and are classified as collisions with ground or water. This particular type of accident can be either of a controlled or uncontrolled nature and the NTSB information does not provide sufficient data with which to define the crash conditions. Miscellaneous accident types, such as a hard landing, undershoot, overshoot, ground swerve, generally do not result in fatalities. For the 1971-73 NTSB data review less than 5 percent of the occupants involved in these types of accident received fatal injuries. This is extremely low by comparison to the overall average of 45.5%, 70.7% and 39% respectively, for the three major accident types shown in Table 2-3.

From the data shown in Table 2-3, of the three major accident types, the most survivable appears to be an accident which is initiated by contact with some obstacle. Possibly one reason for this is that this type of accident occurs at speeds much lower than the airplane's maximum operating level (i.e. near landing, takeoff, low altitude flying) and that the pilot has sufficient time to react and control the airplane's descent to the ground. The most devastating accident for the occupants is the collision

TABLE 2-3. SUMMARY OF ACCIDENT DATA EVALUATION (NTSB DATA 1971 THROUGH 1973)(REFERENCE 7)

Category (a)	Number of Accidents Surveyed	Ratio No. 1 (b)	Ratio No. 2 (c)			Order of Occurrence of Accident Type (Percent Distribution (d))		
			Stall	Collision with Ground	Collision with Obstacle	Stall	Collision with Ground	Collision with Obstacle
1 (<2500)	4502	.122	.428	.654	.325	1(37.5)	3(29.2)	2(33.3)
2 (>2500)	2245	.149	.422	.722	.523	3(22.3)	1(49.1)	2(28.6)
3 (Agriculture)	601	.081	.300	.222	.273	2(39.0)	3(6.5)	1(54.5)
4 (2 Engines)	682	.283	.733	.787	.697	3(21.3)	1(44.3)	2(34.4)
All Categories	8030	.147	.455	.707	.390	3(32.5)	2(33.6)	1(33.9)

(a) See Table 1-4 For Complete Definition of Categories

(b) Ratio No. 1 = (Total Number of Fatalities/Total Number of Occupants) All Accidents

(c) Ratio No. 2 =(Number of Fatalities/Number of Occupants) For a Particular Accident Type Involving an Injury

(d) Accident Types Involving an Injury. Percentage distribution is for the three types shown. Applicable to the Ratio No. 2.

with ground. With the exception of an agricultural airplane, at least 70 percent of occupants that are involved in this type of accident sustain a fatal injury. While collisions with ground represent a wide range of accidents (e.g. forced landings, bad weather, misjudged altitude and/or clearance) it can be assumed that they generally occur at speeds in excess of stall speed and possibly as high as the cruise speed.

The agriculture airplanes (Category 3) which have a takeoff weight comparable to that of the single-engine airplanes used primarily for business, utility, commuter and cargo purposes (Category 2), demonstrate considerably more crashworthiness capability for all the three major accident types. Factors that most likely account for this difference are:

- Agricultural airplanes are designed with specific crashworthy features (overturn pylon, long fuselage, harness, isolated cockpit) that are compatible with their mission.
- Agriculture airplanes may crash under more controlled conditions, usually after hitting some obstacle.
- The pilots of agricultural airplanes generally are more experienced in emergency conditions than the average general aviation pilot.

While the agricultural airplanes provide a greater chance of occupant survivability during a crash, the pilot will sustain a fatal injury in about 30 percent of the accidents in which injuries occur.

The data presented in Table 2-3 indicates that benefits due to improvements in crashworthiness design for the twin-engine airplanes may provide the biggest payoff in reducing the degree of severe or fatal injuries that are sustained relative to the number of people involved. However, on an absolute basis there have been substantially more fatalities in single-engine airplane accidents than in twin-engine airplanes because there are substantially more single-engine airplanes in operation. Therefore, from a life saving point of view, if a priority is to be assigned, emphasis should be placed on upgrading the crashworthiness characteristics of single-engine airplanes.

Table 2-4 sets forth the accident data for the categories wherein a distinction is made between a low-wing configuration and a high-wing configuration and indicates that:

- For the lighter weight single-engine airplanes (<2500 pounds), the high-wing airplane configuration has a higher incidence of fatalities for a stall type accident than the low-wing airplane configuration.

- For the higher weight single-engine airplanes (2500-4000 pounds), the low-wing airplane configuration has a higher incidence of fatalities for a stall type accident than the high-wing configuration.

- The heavier weight low-wing single-engine airplanes (2500-4000 pounds) experience a higher number of fatalities in accidents involving impact with an obstable than do the high-wing airplanes.

- All other comparisons by accident types for high-wing and low-wing single-engine airplanes show approximately ± 10 percent variation from the average of both.

- The comparison of the number of fatalities by accident types for twin-engine high-wing and low-wing airplanes are generally within ± 10 percent of their average except for the case of impact with an obstacle. However, the sample of this type accident in the data bank for the twin-engine high-wing airplane is inadequate for a true comparison.

Ratio No. 2 (Table 2-3) is used in an effort to provide a level of severity of an accident by only including accidents in which injuries occur. Accordingly, the data does not indicate the chances of survival in all accidents. This ratio indicates that "collision with the ground" consistently results, except for the agricultural airplanes, in a high fatality rate. The impact velocities associated with this type of accident are higher and will require the absorption of a greater amount of energy than that of the stall and the obstacle collision types of accidents.

TABLE 2-4. SUMMARY OF ACCIDENT DATA FATALITIES TO OCCUPANTS INVOLVED BY SUBCATEGORIES AND ACCIDENT TYPES (NTSB DATA 1971 THROUGH 1973) (REFERENCE 7)

SUBCATEGORY	NUMBER OF ACCIDENTS (a) SURVEYED	RATIO NO. 2 (b)			AVERAGE VALUE OF RATIO NO. 2 FOR CATEGORY		
		STALL	COLLISON W/ GROUND	COLLISON W/OBSTACLE	STALL	COLLISON W/ GROUND	COLLISON W/OBSTACLE
1A LOW-WING	1595	.25	.598	.347	.428	.654	.325
1B HIGH-WING	2907	.58	.734	.304			
2A LOW-WING	933	.545	.789	.931	.461	.722	.523
2A HIGH-WING	1312	.385	.674	.342			
4A LOW-WING	583	.743	.783	.661	.733	.787	.697
4B HIGH-WING	99	.704	.808	.833			

(a) SEE TABLE 1-4 FOR DEFINITION OF SUBCATAGORIES

(b) RATIO NO. 2 = (NUMBER OF FATALITIES/NUMBER OF OCCUPANTS) (FOR A PARTICULAR ACCIDENT TYPE INVOLVING AN INJURY.

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SECTION 3

OCCUPANT INJURY ASSESSMENT AND PROTECTION

3.1 INTRODUCTION

The purpose of this section is to provide basic information for the designer with regard to:

- Human tolerance to abrupt acceleration
- Available data and indices for assessing occupant injury and/or survivability
- Available crash survival design criteria for the occupants immediate environment
- Available literature on the subject

The data presented in this section has been obtained from the literature, namely References (1) and (2). The information contained in this section has been edited for purposes of this document with the intent of presenting a general overview of human tolerance factors and available techniques for assessing occupant injury. A comprehensive set of background data and reference material is available in Reference 1. While a great deal of effort has been expended in the field of biodynamics and general guidelines have been established, there is still much more valuable data that can be expected in the future.

The following discussions provide general concepts which are applicable to different airplane configurations. However, the details for achieving a satisfactory degree of protection depend on the specific airplane and crash condition.

3.2 HUMAN TOLERANCE TO ABRUPT ACCELERATION

The problem of providing acceptable acceleration limits in the design

for the survivability of occupants is complex and involves the ability to determine and measure the dynamic relationship between the structural system (airframe and restraint system) and the human system (occupant). Data which is used to establish present criteria requires improvement in the following areas:

- Definition of the dynamic response of the restraint system to ascertain the influence on the occupant acceleration levels. Current criteria are based on acceleration measurements at the seat and not on the subject.
- Improved modeling of the human system to account for the critical body modes. Data in this regard is limited and, consequently, so is verification of analytical methods with experience.

The factors that affect human tolerance are:

- Occupant's posture, position and direction relative to the acceleration forces, and the manner in which the occupant is restrained.
- Magnitude and duration of applied force
- Rate of onset of the applied force
- Direction of the applied force

3.2.1 Body Restraint

The method of body restraint has a major effect on human tolerance and, of all the factors affecting human tolerance, is the easiest to control. The effectiveness of the restraint system is dependent upon the area over which the total force is distributed, the location on the body at which the restraint is applied, and the degree to which it limits residual freedom of movement. The greater the contact area between the body and the restraint system, the greater the human tolerance. The restraint system should be located on the body at those points which are best able to withstand the

loads exerted by the decelerative force and which are best able to distribute further the force to the remainder of the body. These points are primarily the pelvic girdle and the shoulder structure. An additional restraint around the rib cage has also been shown to increase tolerance to spineward, eyeballs-out ($-G_x$) accelerations. Restraint systems located over soft tissue tend to be much less effective, often resulting in crushing of the viscera between the restraint system and bony structures. Residual freedom of movement should be limited to an absolute minimum consistent with the necessary comfort and movements required by the duties of the occupant.

When restrained only by the lap belt, the occupant's tolerance to abrupt acceleration is relatively low. In forward-facing seats, a longitudinal impact will cause a rotation of the upper torso over the belt, a whipping action of the head, and often impact of the upper torso on the legs, resulting in chest injuries. Head injuries due to impacts with the surrounding environment are also very common for occupants restrained only with lap belts. When longitudinal forces are combined with a vertical component, there is a tendency for the occupant to slip under the belt (submarine) to some degree. This can place the belt up over the abdomen. The longitudinal component of the pulse then causes the upper torso to flex over the belt, with the restraining force concentrated at some point on the spine and not on the pelvic girdle. In this configuration, tolerance is extremely low.

A conventional lap belt and shoulder harness configuration greatly reduces injuries from head impacts and helps to maintain proper spinal alignment for strictly vertical impact forces. This configuration is unsatisfactory, however, for impacts with both vertical and longitudinal components. Pressure by the upper torso against the shoulder straps causes these straps to pull the lap belt up into the abdomen and against the lower margin of the rib cage. This movement of the lap belt allows the pelvis to move forward under the lap belt, causing severe flexing of the spinal column. In this flexed position the vertebrae are very susceptible to anterior compression fractures. A lap-belt tie-down strap prevents raising of the lap belt by the shoulder harness and nearly doubles the tolerance to impact

forces.

The amount of slack in the restraint system can affect tolerance to a given acceleration pulse. In general, the more rigid the link between the occupant and the seat, the greater the occupant's tolerance to an abrupt acceleration. A loose restraint system can result in the occupant receiving a magnification of the accelerative force applied to the seat. The inertia of the occupant will cause him to maintain a near constant velocity, independent of the decreasing velocity of the seat, until the slack in the restraint system is taken up. As this point is reached, the velocity of the occupant is abruptly reduced to that of the seat at relatively high G levels, even exceeding that of the seat. This is often referred to as "dynamic overshoot." Dynamic overshoot is a complex phenomenon involving the elasticity, geometry, mass distribution, and thus the natural frequency of the occupant restraint and seat system.

3.2.2 Magnitude, Duration, Rate and Direction

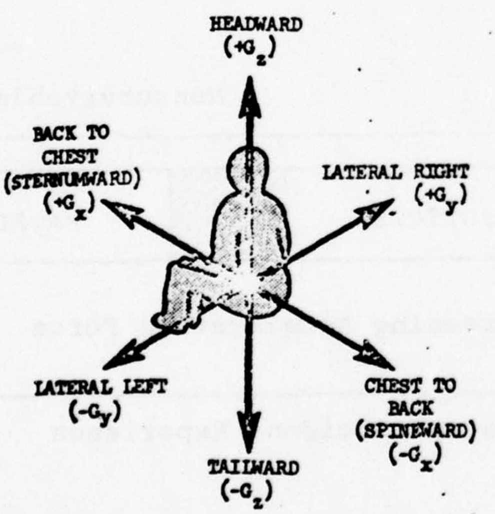
Reference (3) provides a comprehensive survey of the literature regarding the subject of human tolerance to rapidly applied accelerations. The information presented in this report is often used as a basis for relating the crash environment to human tolerance levels. The acceleration peaks, durations and rates of acceleration onset for various directions of acceleration are summarized in Table 3-1. Curves showing duration versus magnitude and acceleration rates for load applied in the four directions noted in Table 3-1 are available in References 1 and 3.

TABLE 3-1. SUMMARY OF HUMAN TOLERANCE LEVELS FOR PEAK VALUES, DURATION AND RATES OF ACCELERATION (REFERENCES 1 and 3)

Acceleration[a] Direction	Voluntary Human Exposure		Human Tolerance Limit		Rate of Acceleration Onset (g/sec)
	Peak Acceleration (g)	Duration (second)	Peak Acceleration (g)	Duration (second)	
Sternumward (fwd)	35	.04	83	.04	1150
			45	.10	
Spineward (aft)	45	≤.044	45	.10 (b)	600 (b)
			25	.20	
Headward (up)	16	≤.04	25	.10	115
Tailward (down)	10	.01	15	.01	80
Lateral (side)			12-20	.1	

(a) The direction of the acceleration forces obtained from Reference (1) is presented in Figure 3-1.

(b) For extremely short durations (i.e. free falls) onset rates of 28000 g/sec are tolerable.



DIRECTION OF DECELERATIVE FORCE

VERTICAL

Headward - Eyeballs down
Tailward - Eyeballs up

TRANSVERSE

Lateral Right - Eyeballs left
Lateral Left - Eyeballs right
Back to Chest - Eyeballs in
Chest to Back - Eyeballs out

Note:
The decelerative force on the body acts in the same direction as the arrows

Figure 3-1. Decelerative Forces On The Body (Reference 1)

The data presented in Table 3-1 is for tolerance levels which, if exceeded, could result in serious injury and are based on the occupant restrained with the maximum support (i.e. lap, shoulder, thigh and chest straps).

From the data presented in Table 3-1 it can be seen that human tolerance to abrupt accelerations varies significantly with respect to the direction in which the force is applied to the body. The body is able to withstand much more force when this force is applied perpendicular to the long axis of the body in a forward or backward direction (G_x) than when applied parallel to the long axis (G_z). Human tolerance to loads applied laterally (G_y) has not been fully explored.

Accelerative forces can be generally divided into the tolerable, injurious, and fatal ranges according to their effect on the body as shown in Figure 3-2.

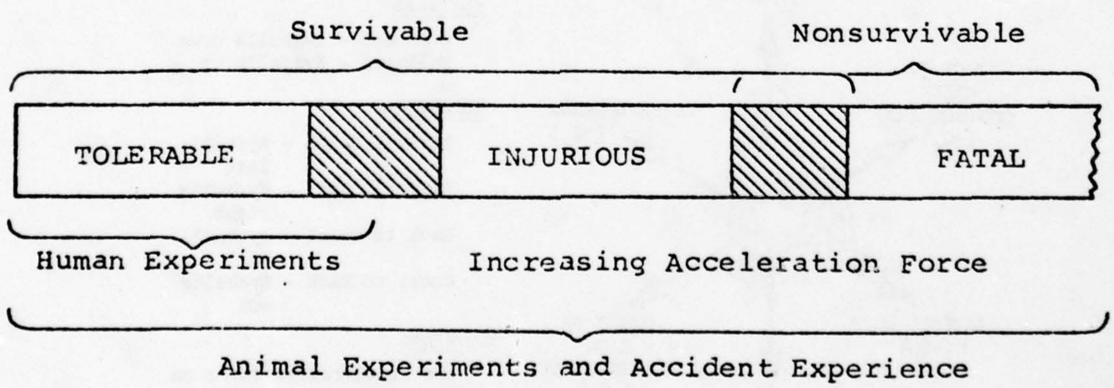


Figure 3-2. Range of Accelerative Forces (Reference 1)

Figure 3-2 shows that forces in the tolerable range are such that minor trauma such as abrasions and bruises may occur bit the subject is not incapacitated. Forces in the injurious range cause moderate to severe trauma which may or may not incapacitate the subject, and survival is insured with prompt medical care. This range appears to be compatible with the tolerance data discussed previously. Forces in the fatal range cause nonsurvivable trauma.

The tolerance data presented in Figure 3-1 shows that tolerance is a function not only of the acceleration level and rate of application but also of duration. For this reason, it is not possible to completely define tolerance in terms of a single G value and duration. Several methods for evaluating severity of environments in terms of human tolerance have been developed for use as indicators. The methods involve calculating a number through mathematical treatment of several variables and then empirically relating the number to human injury. This number is then referred to as an injury or severity index.

3.3 SEVERITY INDICES

It is generally useless to talk of impact data and response in oversimplified parameters because, in a mechanical sense, the human body is a complex, nonlinear, damped, multi-mass system. As such, it is subject to dynamic response in any of its many modes of vibration. This means that the response or actual acceleration time history experienced by the body, or a portion thereof, may differ markedly from the acceleration time input to the body applied at the point of impact. The problem has been to define some form of parameter which is indicative of the degree of severity of a particular input excitation. Various indicators have been developed, and two are discussed herein.

3.3.1 Weighted Impulse Criterion (Gadd Severity Index)

It can be seen from human tolerance data presented in Table 3-1 that high forces or accelerations can be tolerated for only very short periods of time while lower values of these quantities can be tolerated for longer periods of time. Figure 3-3 shows this relationship for brain injury in forehead impacts. It illustrates the dependency of acceleration tolerance upon time duration. The Society of Automotive Engineers has accepted the weighted impulse criterion for evaluating the injury potential of an impact. Under this criterion, injury potential is proportional to the equation

$$SI = \int_{t_o}^{t_s} a^n \, dt \qquad (3\text{-}1)$$

where
- SI = severity index
- a = acceleration as function of time
- n = weighting factor greater than 1
- t = time
- t_o = initial time
- t_s = final time

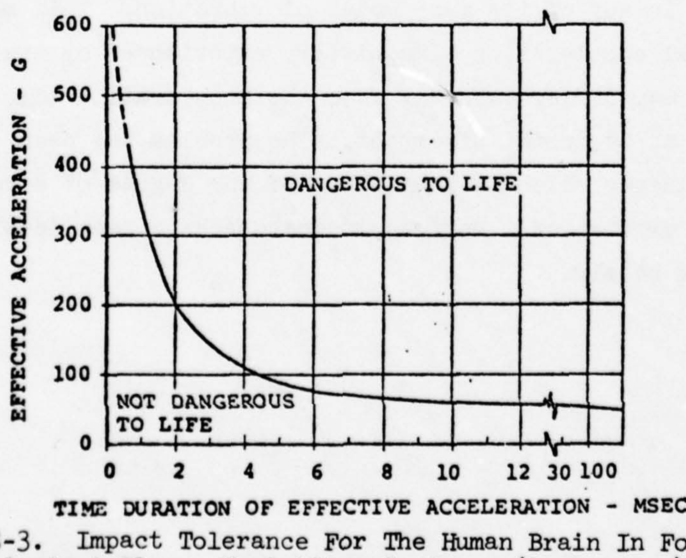


Figure 3-3. Impact Tolerance For The Human Brain In Forehead Impacts Against Plane, Unyielding Surfaces (Reference 4)

Published data indicate that a weighting factor should place relatively greater weight upon the acceleration than upon the duration. This is particularly true of skeletal components, which are less viscoelastic than soft tissue. The index may be obtained graphically by dividing the time base of the acceleration-time curve into sufficient segments to define the acceleration curve. The G value then read from the curve for the center of the increment is raised to the 2.5 power, and the result is multiplied by the time increment. The sum of all the values obtained gives the severity index. A severity index sample calculation is shown in Figure 3-4.

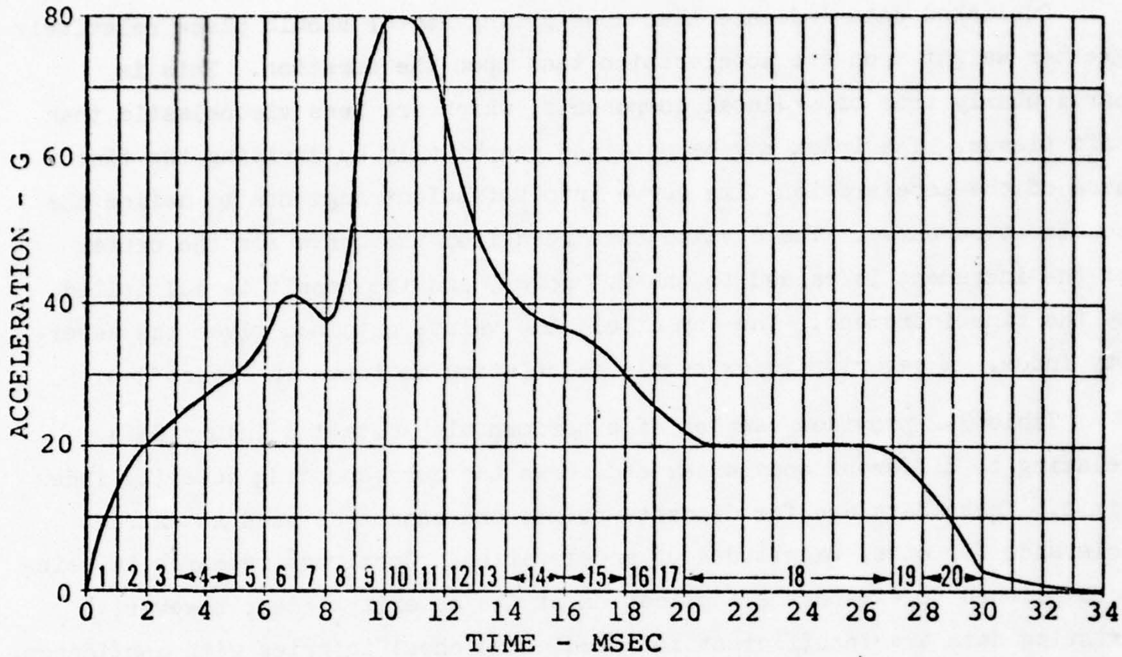
Table 3-2 provides samples of experimentally obtained injury data relating to different body areas and shows the corresponding severity index limit. These data are for discrete points and cannot be used to extract tolerance for other magnitudes of acceleration. Continued research is being accomplished to expand the application of the severity index; however, existing data are insufficient for predicting chest injuries with confidence.

3.3.2 Dynamic Response Index (DRI)

The human response to short-duration accelerations applied in the upward vertical direction parallel to the spine ($+G_z$) has been modeled by a single lumped-mass, damped-spring system as shown in Figure 3-5. In this model it has been assumed that the total body mass that acts upon the vertebrae to cause deformation is represented by the single mass. In use, the relationship

$$\frac{d^2\delta}{dt^2} + 2\,\zeta\omega_n \frac{d\delta}{dt} + \omega_n^2\delta = Z \qquad (3\text{-}2)$$

is solved through the use of a computer. The third term is representative of the deformation of the spine and when divided by g is referred to as the Dynamic Response Index (DRI). The model is used to predict the maximum deformation of the spine and associated force within the vertebral column for various short-duration acceleration inputs. The properties used in the



Calculations

Increment No.	Time of Increment (sec)	Midpoint G Value	$G^{2.5}$	Incremental SI Index (Time x $G^{2.5}$)
1	0.001	7	130	0.13
2	0.001	18	1,400	1.40
3	0.001	23	2,500	2.50
4	0.002	27	3,800	7.60
5	0.001	33	6,300	6.30
6	0.001	40	10,000	10.00
7	0.001	38	8,800	8.80
8	0.001	47	15,000	15.00
9	0.001	75	48,000	48.00
10	0.001	80	57,000	57.00
11	0.001	73	46,000	46.00
12	0.001	56	23,000	23.00
13	0.001	43	12,000	12.00
14	0.002	37	8,300	16.60
15	0.002	33	6,200	12.40
16	0.001	27	3,800	3.80
17	0.001	24	2,800	2.80
18	0.007	20	1,800	12.60
19	0.001	17	1,200	1.20
20	0.002	10	330	0.66
			Severity Index	287.79

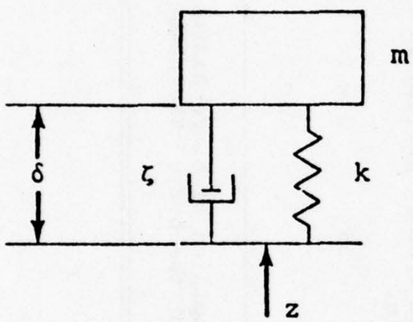
Figure 3-4. Sample Calculation Of A Severity Index (Reference 4)

TABLE 3-2. EXPERIMENTALLY DETERMINED LEVELS OF IMPACT, PRODUCING MINOR TO MODERATE INJURY (RESPONSE FUNCTION)(REFERENCE 4)

Body Area Impacted	Minimum Contact Area (sq. in.)	Effective Weight (lb)	Peak Force (lb)	Peak (g)	Severity Index Limit	Conditions Used To Obtain Tolerance Data
Face* (localized loading	4	15	600	40	400	Smooth, collapsible, padded surface, with accelerometers mounted on bone opposite impact
Face* (distributed loading)	15	15	1200	80	1000	
Throat	2		150**	-	-	Force distributed with deforming pad
Brain (skull)	3	15	1500	100	1000	Various surfaces with accelerometers mounted as with "face"
Chest	30	75	1500	-	-	Load cell mounted to comformable chest contact surface
Side Above Pelvis, Below Ribs	10	75	Maximum dynamic protrusion into subject area of 1.25 in.			
Knee-Thigh-Hip Complex (load applied through knees)	3	40	1400	35	-	Load cell mounted to conformable chest contact surface

*Below eyebrows.
**This is considered to be a reasonable value in the opinion of biomechanics investigators, based on the strength of similar human structure throughout the body. The number may be modified as better data are gathered.

model were derived from human samples or tests. The spring stiffness was determined from tests of cadaver vertebral segments; damping ratios were determined from measurements of mechanical impedance of human subjects during vibration and impact.



m = mass (lb-sec^2/in.)

δ = deflection (in.)

ζ = damping ratio

k = stiffness (lb/in.)

z = acceleration input (in./sec^2)

$$\text{*DRI} = \frac{\omega_n^2 \, \delta_{max}}{g}$$

ω_n = natural frequency of the analog = $\sqrt{k/m}$ (rad/sec)

g = 386 in./sec^2

*Dynamic Response Index

Figure 3-5. Spinal-Injury Model (Reference 6)

A correlation of the cumulative probability of spinal injury versus DRI is shown in Figure 3-6 (6). In this figure, the cumulative probability of injury is plotted against DRI for both cadaver data and operational data. It is seen that the injury probability does vary with the DRI but that the cadaver data show a higher probability of injury than do the operational data. It would be expected that the intact, living vertebral column imbedded in the torso would be stronger than cadaver segments; consequently, this result might be predicted.

The Air Force has adopted a system using a combination of acceleration

as a function of duration and the DRI for establishing acceptable ejection seat acceleration environments. In specification MIL-S-9479A(USAF), the acceleration levels to be imposed on the seat occupant are controlled by a combination of acceleration, time, and DRI as shown in the following relationship:

$$1 \geq \sqrt{\left(\frac{DRI_Z}{G_{Z_L}}\right)^2 + \left(\frac{G_X}{G_{X_L}}\right)^2 + \left(\frac{G_Y}{G_{Y_L}}\right)^2} \tag{3-3}$$

Here G_X and G_Y are measured acceleration magnitudes in the X and Y directions and G_{Z_L}, G_{X_L}, and G_{Y_L} are the limit acceleration parameters as read from acceleration versus time curves also included in the specification. DRI_Z is the DRI computed from equation 3-2 for the positive Z direction. The computed value for the right-hand term of equation 3-3 may not exceed 1.

The DRI is calculated from equation 3-2 with model coefficients for the positive spinal case (eyeballs down) defined for the mean age of the Air Force flying population (age 27.9 years). The model coefficients are as follows:

$$\omega_n = 52.9 \text{ rad/sec}$$

$$\zeta = 0.224$$

The DRI has been shown to be effective in predicting spinal injury potential for $+G_Z$ acceleration environments. Although work is being done to apply the DRI to the other directions, confidence in predictions is hampered by difficulty in establishing injury threshold because of the many possible modes of injury and variations in tolerance to these modes.

The application of a severity index to assess occupant injury should be weighed with regard to the type of accident that is involved. For example in an impact involving large longitudinal forces and small vertical forces, the DRI is of little value since it is applicable only to vertabrae compression type injuries.

TYPE OF AIRCRAFT	NUMBER OF SUCCESSFUL EJECTIONS
T-37	42
F-100	64
F-104	51
F-105	57
F-4C	76
F-4B	31

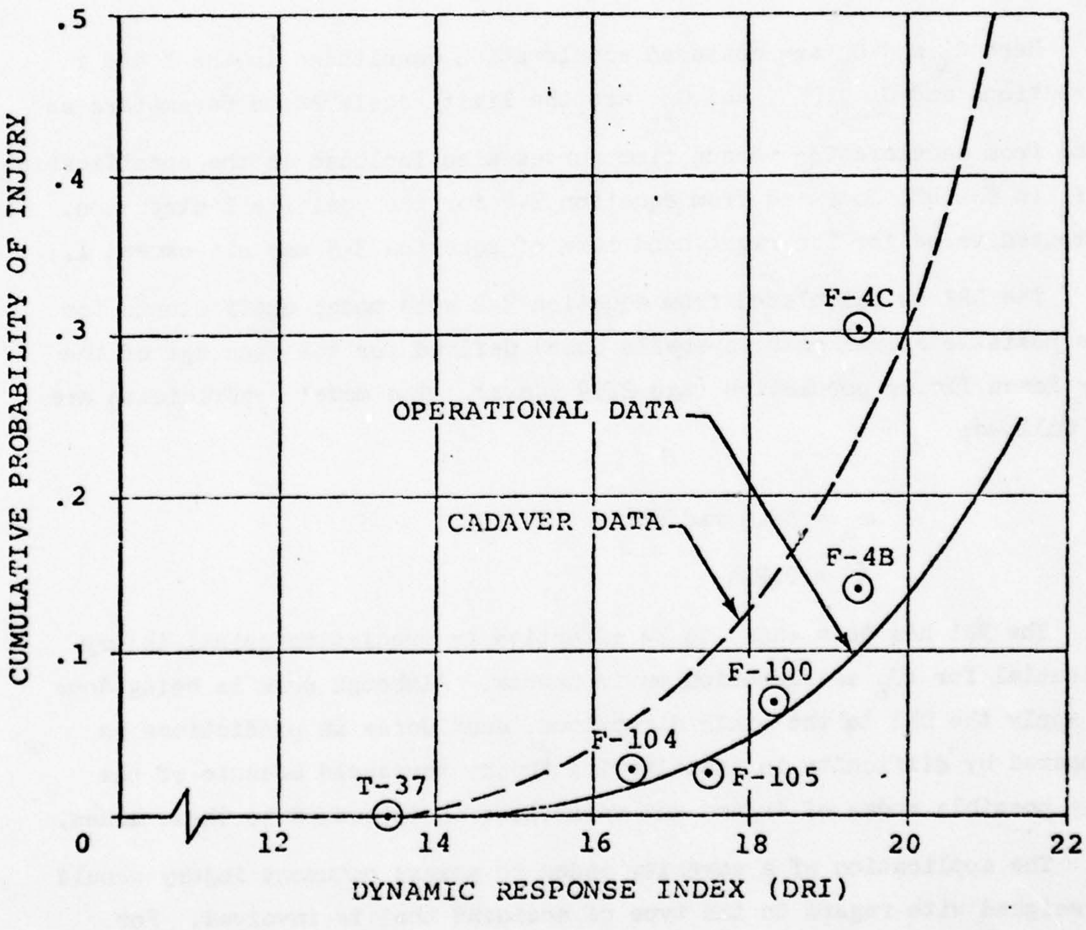


Figure 3-6. Probability of Spinal Injury Predicted From Cadaver Data Compared To Operational Experience (Reference 6)

3.4 OCCUPANT PROTECTION

Protection of an occupant in the front seat(s) in a survivable accident depends primarily upon the occupant's use of a seat belt/shoulder harness restraint system. Means for providing protection from head and torso injury are desirable for the times that the occupant fails to use the shoulder harness portion of the restraint system, as it is impractical to place occupants where they cannot strike the aircraft structure.

3.4.1 Environmental Hazards - General

3.4.1.1 Primary Hazards

The primary environmental hazards are those rigid or semirigid structural members within the extremity envelope of the head and chest.

3.4.1.2 Secondary Hazards

Secondary environmental hazards are those that could result in trapping or injuring the lower extremities to the extent that one's ability to escape rapidly would be compromised.

3.4.1.3 Tertiary Hazards

Tertiary environmental hazards are those rigid and semirigid structural members that could cause injury to flailing upper limbs to an extent that could reduce one's ability to operate escape hatches or perform other essential tasks.

3.4.1.4 Upper Torso Vulnerability

It can be seen in Figures 3-7 through 3-12 that the strike envelopes allow considerable upper torso movement for various seating and restraint configurations. Since the upper torso, and particularly the head, is the most vulnerable part of the body, it is a necessity that maximum protection be provided within its strike envelope.

3.4.1.5 Lower Extremity Movement

The movement of unrestrained lower extremities in a crash impact is not significantly influenced by type of body restraint. Consequently, even with an optimized body restraint system, those areas within the lower extremity strike envelope must include ample protection design.

3.4.2 Extremity Strike Envelope

Figures 3-7 through 3-12 were obtained from Reference 1. They show the body extremity strike envelopes for a fully restrained occupant and an occupant restrained only by a seat belt. The strike envelopes are based on the following parameters:

a. Ninety-fifth percentile U.S. Army personnel.

b. Four g accelerations with human subjects; higher accelerations would change the strike envelopes slightly.

c. Four inches of lower torso movement away from the seat both forward and laterally (an approximation based on crash test data).

d. Four inches of upper torso movement away from the seat back both forward and laterally when restrained by seat belt and shoulder harness (an approximation based on crash test data).

e. Head movement upward is a possibility in certain impact situations.

The dashed lines in the forward and sideward extremity envelopes show an approximate head movement for a situation of this type.

3.4.3 Head Impact and Whiplash

Concussion is an important aspect of human tolerance. Concussion of only short duration can temporarily immobilize an individual and reduce his chances of survival by subjecting him to postcrash hazards such as fire or drowning.

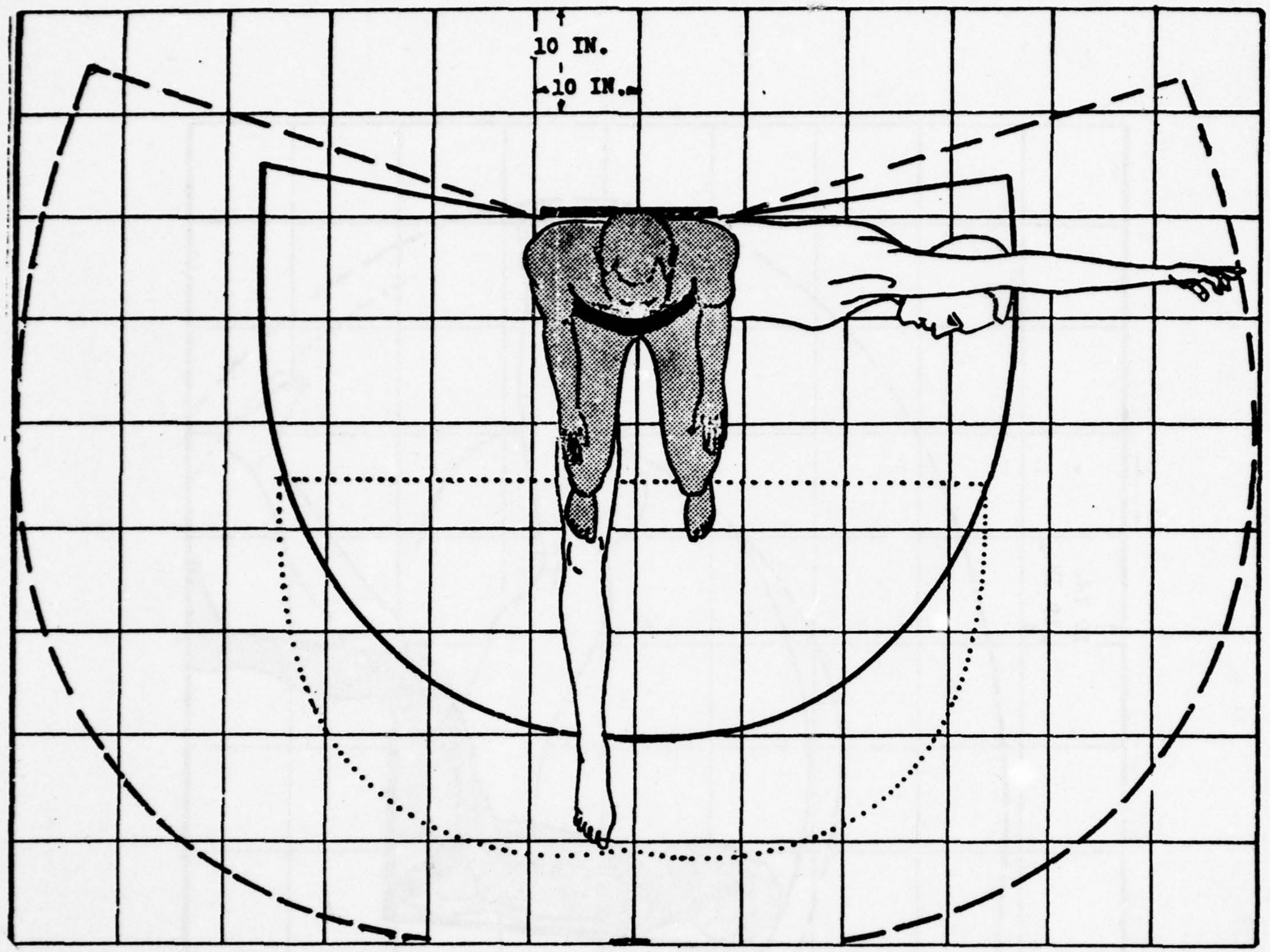


Figure 3-7. Seat-Belt-Only Extremity Strike Envelope - Top View (Reference 1)

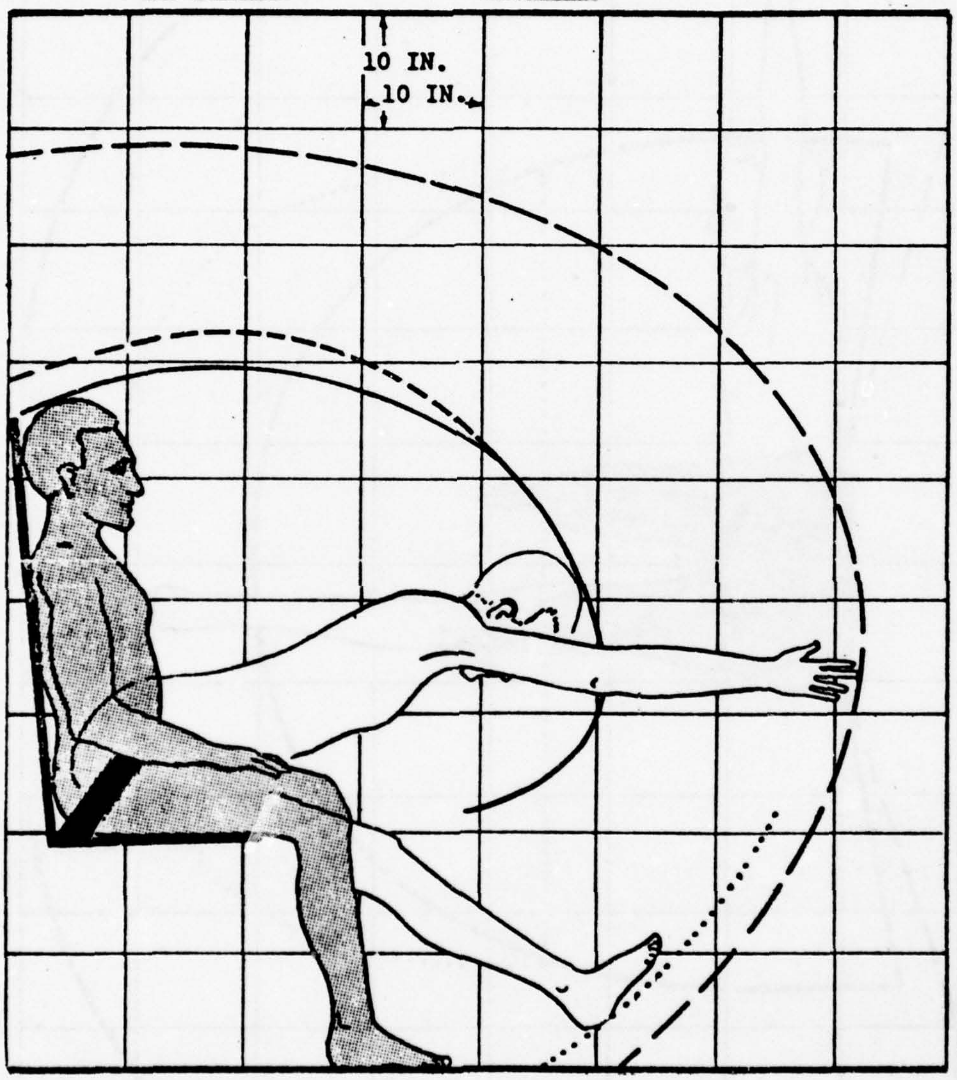


Figure 3-8. Seat-Belt-Only Extremity Strike Envelope - Side View (Reference 1)

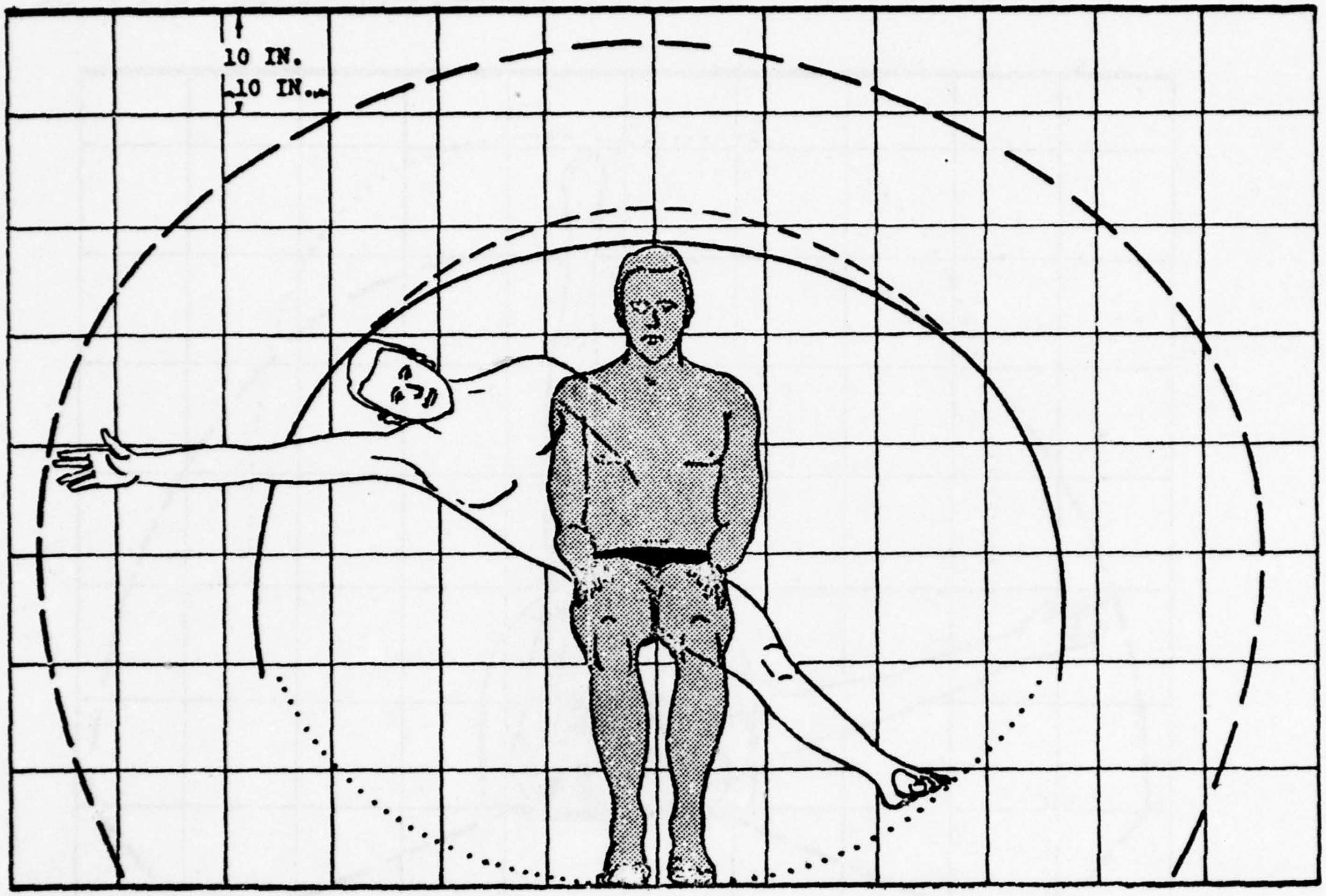


Figure 3-9. Seat-Belt-Only Extremity Strike Envelope - Front View (Reference 1)

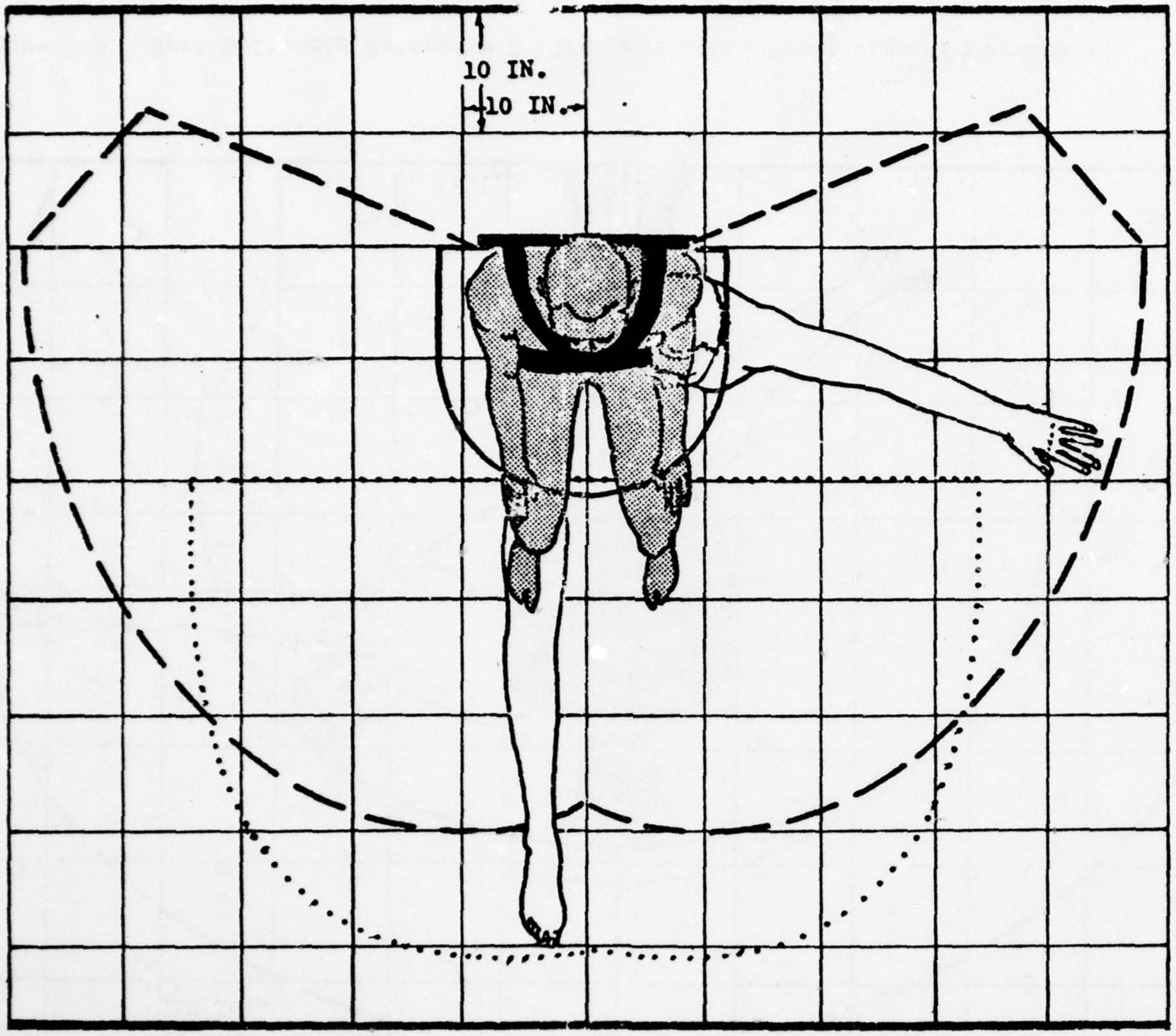


Figure 3-10. Full-Restraint Extremity Strike Envelope - Top View (Reference 1)

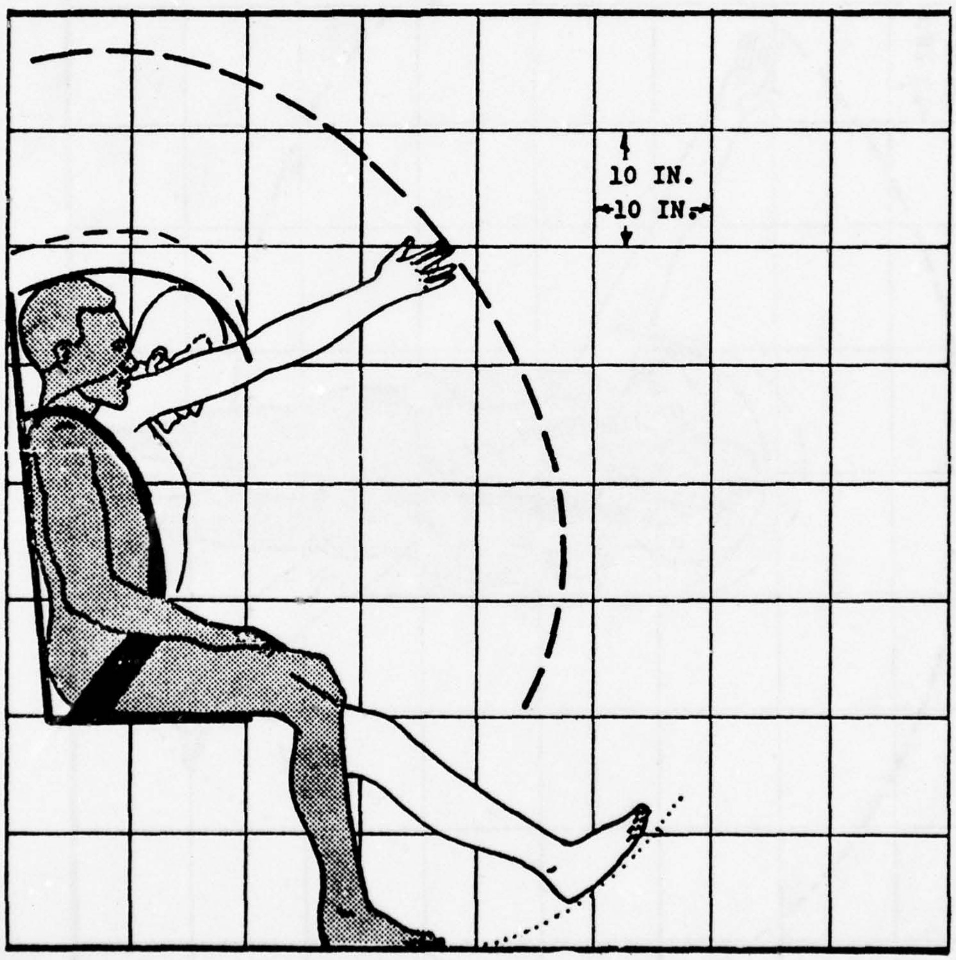


Figure 3-11. Full-Restraint Extremity Strike Envelope - Side View (Reference 1)

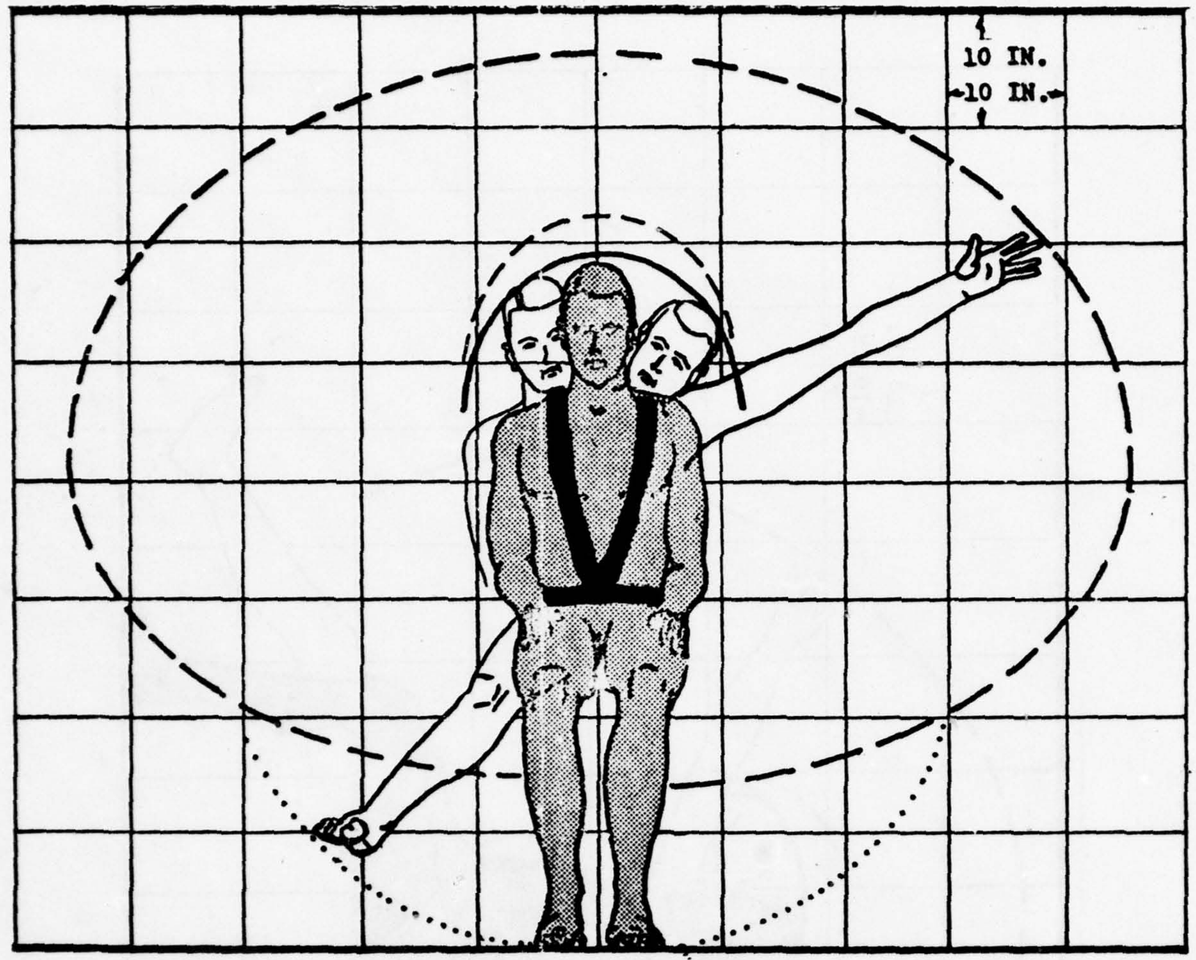


Figure 3-12. Full-Restraint Extremity Strike Envelope - Front View (Reference 1)

The study described in Reference (7), indicates that approximately 50 percent of the potential for brain injury in an impact to the unprotected head is directly proportional to head rotation and inversely proportional to head translation resulting from the impact. The other 50 percent is directly proportional to the contact phenomena of the impact.

According to a hypothesis developed by Holburn,[8] shear stresses induced by head rotation can produce concussion. It is shown in Reference 21 the relationship between damaging velocity and damaging acceleration is:

$$\dot{\theta}_o = \frac{\ddot{\theta}_o}{\omega} \tag{3-4}$$

where $\dot{\theta}_o$ = damaging rotation velocity, rad/sec

$\ddot{\theta}_o$ = damaging rotation acceleration, rad/sec^2

ω = natural frequency of rotation of brain, rad/sec

Scaling factors needed to predict concussion thresholds for man from data taken on subhuman primates were developed in Reference (9). This study showed that $\ddot{\theta}_o$ can be represented by the equation

$$\ddot{\theta}_o = \frac{c}{m^{2/3}} \tag{3-5}$$

where m = mass of the brain, gm

c = an experimentally derived constant, gm$^{2/3}$ rad/sec^2

as energy-absorbing padding provided that sharp corners and protrusions are eliminated and the structure/head contact area is large. When the design layout is free of sharp or small radius corners, edges, and protrusions, attention can be given to design for controlling the magnitudes of the acceleration pulses to which the head may be subjected.

Head acceleration is a function primarily of (a) head striking velocity, (b) head/torso mass, and (c) stopping distance. Head striking velocity is a function of (a) body geometry, (b) method of restraint (lap belt only or

The investigators found $c = 2.16 \times 10^5 \ gm^{2/3} \ rad/sec^2$ and further showed that the relationship

$$\dot{\theta}_o = \frac{\ddot{\theta}_o}{\omega} \qquad (3\text{-}6)$$

produced reasonable agreement between predictions and empirical data. Limiting values thus predicted to produce a 50 percent probability of concussion in a man having a brain mass of 1300 grams are as follows (Reference 7):

$$\ddot{\theta}_o = 1800 \ rad/sec^2 \qquad (3\text{-}7)$$

$$\dot{\theta}_o = 50 \ rad/sec$$

Studies by AvSER and Wayne State University indicate that head impacts at more than 20 fps are not readily tolerated by humans unless the structure has been adequately covered with energy-absorbing material. However, ductile or deforming energy-absorbing structure or construction can be as effective

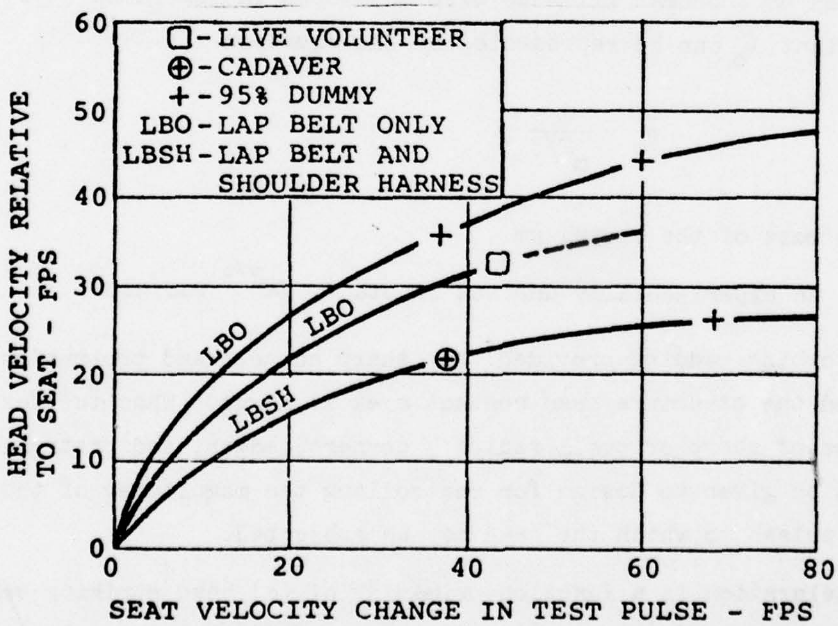


Figure 3-13. Measured Head Velocities In Sled Tests With Anthropomorphic Dummies And Cadavers (Reference 1)

both lap belt and shoulder harness), and (c) seat velocity change. Figure 3-13 shows typical head velocities relative to the seat as measured on anthropomorphic dummies, cadavers, and human volunteers in dynamic seat tests using (a) lap belts only, and (b) both lap belt and shoulder harness.

Figure 3-14 shows an approximate correlation between head impact velocity, crushable material thickness (stopping distance), and average acceleration. The material thickness given in this figure is based upon an assumed rectangular acceleration-time pulse and is, therefore, the minimum material thickness suitable under ideal conditions.

Figure 3-15 shows an acceleration-time plot of the average acceleration versus the total period of the impulse required to approach unconsciousness limits. This plot was reported by Dr. Gurdjian and others of Wayne State University after extensive experiments with cadavers and live animals in their work on skull fracture and concussion.

Design criteria applicable to padding material is presented in Section 5 of Reference 1. The reader is referred to Reference 1 for data regarding typical material behavior and applicable references.

3.4.4 Torso Impacts

Figures 3-8 and 3-9 show the approximate flailing area for an occupant restrained only by a lap belt. Control wheels, control columns, pedestals and instrument panels are primary impact hazards to an unrestrained torso. Since the upper torso, particularly the head, is a most vulnerable part of the body, it is necessary that protection be provided within its strike envelope. Head impacts against local structure are a primary cause of serious injury. Protection for the head can be provided in the form of protective helmets and/or upper torso restraint and energy-absorbing structure in the occupant's immediate environment. Under certain conditions, even the forces incurred in minor crash impacts can cause serious or fatal injuries.

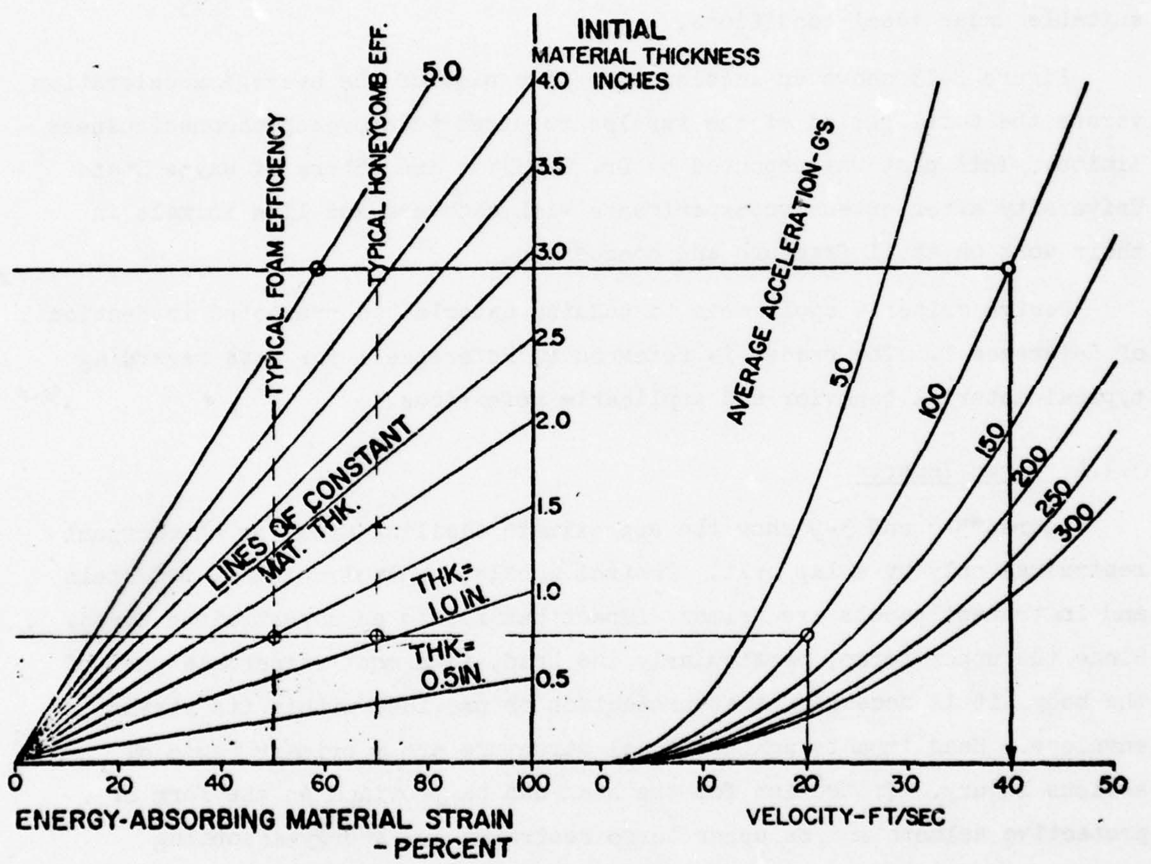


Figure 3-14. Crushable Material Thickness As A Function Of Velocity Change And Acceleration Level (Reference 10)

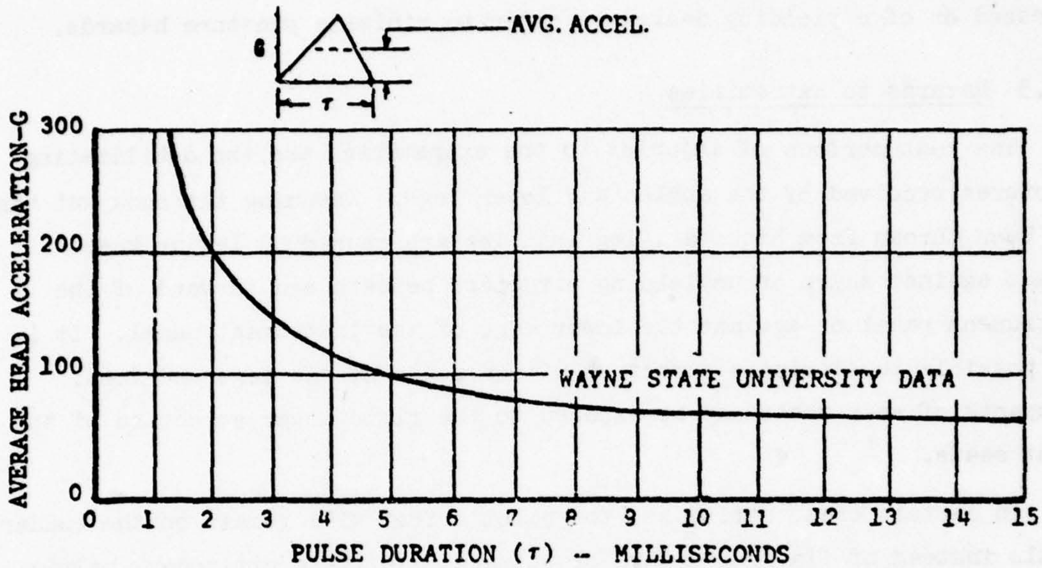


Figure 3-15. Head Tolerance To Impact As A Function Of Pulse Duration As Published By Wayne State University (Reference 1)

A floor mounted control column can present a serious hazard if in failing the column impacts with the flailing torso/head. Such failure, especially if it is jagged or sharp, can cause serious injuries to an occupant thrown against it.

Horizontal, instrument-panel-mounted control columns can be the cause of serious or fatal injuries, especially if the column breaks or if the control wheel fails. Some horizontal, panel-mounted control columns have failed by bending over double to form a sharp projection in front of the occupant's chest.

The use of ductile rather than brittle materials will allow deflection of the control wheel structure under impact and prior to failure. Control wheels with provisions for large padded areas would, even after failure, minimize injuries due to chest penetration by the column.

Controls should be so designed as to minimize sharp edges. Where practicable, surfaces should be padded and controls should be either recessed or of a yielding design in order to minimize puncture hazards.

3.4.5 Hazards to Extremities

The most serious of injuries to the extremities are the debilitating fractures received of the ankles and lower legs. Assuming the occupant has not been thrown from his seat, leg injuries are caused by leg or knee impact against sharp or unyielding structure beneath and forward of the instrument panel or against the lower edge of the instrument panel. It is not possible to eliminate structure within reach of the legs and feet. Occupants of rear seats may be exposed to the rigid lower structure of the front seats.

In certain crash attitudes, the pilot's feet will remain on the rudder pedals instead of flailing upward or outward. In these attitudes, pelvic rotation around the seat belt can occur. This pelvic rotation has the effect of forcing the pilot's feet hard against the rudder pedals, and can occur even if the lap belt is drawn up tightly. The tendency is aggravated by a loose or slack lap belt.

3.4.6 Equipment

In any accident, loose items or fixed equipment can become lethal missiles. Accidents have occurred in which occupants have been injured by loose equipment, some by direct injury and others by seat failure caused by the impact of equipment or baggage. Loose equipment and baggage can block or impede evacuation. It is, therefore, desirable that all items of equipment or baggage carried in the cabin (especially those items aft of the occupants) be installed or stored securely.

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SECTION 4

STRUCTURAL DATA AND METHODS

4.1 INTRODUCTION

This section contains a discussion regarding procedures and data that are available and applicable to structural crashworthiness design. Comprehensive literature survey matrices relating references to selected subject matter are presented in References 1 and 2. The information obtained from past literature surveys is utilized in this section. While some of the data contained in this section is obtained from rotary wing aircraft studies, the information is presented because it is pertinent to general aviation airplane designs. The amount of test and analytical data that has been compiled through the years is obviously too vast to incorporate in one section of any report. Consequently, selected topics and illustrative samplings of available data are presented. The references at the end of this section provide the user with an indication of the type and amount of data that is available.

4.2 ANALYTICAL METHODS

There are various analytical approaches that can be applied to structural crashworthiness analysis. One approach involves utilizing computer technology to treat complex behavior involving large nonlinear deflections. Generally this approach involves establishing a relatively large math model to idealize structure and its behavior. The accuracy of results that are obtained depend to some extent on the rigor that is employed. Analytical techniques can be used to identify finite or gross behavior. Furthermore, they can be oriented toward different phases of design such as preliminary or final. Practical, simplified approaches to obtain approximate behavior are desireable, provided they are of sufficient accuracy for the purposes intended, since they would

normally offer an economic advantage. As a rule,one would anticipate that simplified approaches can be most effective in identifying structural behavior which in turn can be used as potential inputs to more complex computer analysis. Regardless of which analytical approaches are selected, whether for substructures or complete vehicles, the solutions are only approximate. Consequently, rigorous or simplified analyses differ primarily in the degree of accuracy that is desired, the amount of information that is available, and the economy of operation that is associated with each approach.

4.2.1 Computer Technology

There are several methods which are potentially applicable to the development of computer programs which can be used for predicting dynamic crash behavior with sufficient accuracy for the purpose of developing design criteria and preliminary concepts for improved crashworthiness of general aviation aircraft. The primary methods of analysis are generally referred to as lumped mass, normal mode, finite element, finite difference and static-plastic analysis. Static-plastic analysis is applicable to most structures, particularly beam and simple shell type structures. However, since it is not geared to treat dynamic problems wherein instabilities and/or buckling failures occur, it would appear to be limited for vehicle crash analysis. The dynamic mode approximation technique, while relatively simple to apply, is limited in that; (a) a constant acceleration is assumed throughout the dynamic deformation and therefore the use of load-deflection characteristics obtained by this approach would not accurately reflect the actual acceleration response of the structure, (b) this technique is not applicable to structure which exhibits instability and/or buckling characteristics, and (c) for complex structures it is difficult to define a unique mode shape which is kinematically and dynamically admissible.

Finite-difference and finite-element techniques are discussed in many references, including (47) through (51) to list a few. The finite element solution is essentially the same as a lumped mass solution, i.e., it

involves converting continuous mass elements into discrete mass elements interconnected by springs. However, a finite element program is written such that the input is in terms of the characteristics of common structural elements such as beams and plates. The main concern in using a finite element solution would be the ability to handle nonlinearities easily and perform the analysis within a reasonable program run time. The finite-difference technique differs from the finite-element approach in the manner by which the constitutive equations representing force-deflection relationships are described. As the name implies, small differences are used in the representation of elements which are bounded by other elements or are constrained in some manner. These two approaches give reasonable load-deformation information for simple structures. However, for complex structures, these numerical methods are not yet considered as reliable or as economical as experimental techniques. In general finite element analytical techniques and numerical methods for stability analysis and post-failure analysis presented in the literature are primarily concerned with the techniques rather than the application of the technique to practical problems.

Thus far, the lumped mass and normal mode approaches have been used in analyzing the behavior of complete aircraft structures during a crash condition. The lumped mass approach appears to be more capable of predicting general large-scale deformation than the normal mode approach. The normal mode approach requires a redefining of the element stiffnesses (also required in the lumped mass method) and then a recomputation of the system frequencies and modes shapes for every increment of time in the nonlinear regime. The determination of frequencies and mode shapes requires the solution of coupled equations which necessitates a time consuming matrix inversion. Since in a crash analysis the nonlinear deflection is the most important aspect of the problem, the additional computational requirements of the normal mode approach will be less efficient and will introduce potentially significant inaccuracies as compared to the lumped mass method. The use of the finite element method in conjunction with a lumped mass system would appear to offer some potential.

The use of a lumped mass analysis to perform a dynamic analysis to evaluate the crash response of fixed wing aircraft is described in References 3 and 4. In Reference 3 the modeling of the fuselage of a typical fixed-wing transport for a crash is described. The airplane model allows for pitch and vertical translation. A series of nonlinear partially restoring springs represents the crushing of the lower fuselage. Up to six fuselage bending normal modes are input. Longitudinal motions are not considered; hence, no plowing or friction drag forces are computed. The program numerically converts the input load-deflection curves into load-time curves and utilizes closed-form solutions for the degrees of freedom within each time increment. No aerodynamics are included. Test case results using six normal modes indicate that structural flexibility may play an important role in crash load determination.

In Reference 4 the modeling of the Lockheed Constellation 1649 for crash landing is described. A symmetrical model (pitch, plunge, fore-aft) is employed, with one fuselage vertical bending normal mode. Vertical springs are distributed longitudinally along the bottom of the fuselage. Each spring constant is a function of vertical deflection, with three separate deflection regions defined. These regions are the initial elastic range, the plastic range, and an increasing stiffness range representative of floor and wing stiffening at large vertical deflections. Ground plowing and friction forces are included,as are fuselage longitudinal vibrations. The results shown in Reference 4 indicate that the inclusion of structural flexibility has little effect on the results; rigid-body motions tend to dominate. This conclusion differs with the conclusion presented in Reference 3.

In Reference 1 the results of a lumped-mass analysis of a helicopter crash test, wherein combined vertical and lateral impact velocities are involved, are shown to compare favorably with the test data. The analysis was able to accurately duplicate the maximum deflections, permanent deformations, major mass acceleration responses, vehicle motions and change in energy as obtained from the test data.

4.2.2 Simplified Analytical Techniques

Depending on the level of software program that is developed, the user

may not have the manpower, capital or data resources necessary to perform complex analysis. The use of simpler, more easily understood techniques requiring readily available data can be more desirable even if the sacrifice of some accuracy were to be involved.

The determination of load deformation characteristics of aircraft structure will enhance the ability of the designer to predict structure and occupant responses during severe yet survivable crashes. However, it is important that this data is presented in a manner which will aid the designer in developing the desired level of crashworthiness in the airframe structure. The data presented in the literature provides analytical procedures and/or empirical data which is applicable to a great many types of structural elements. Unfortunately, much of the data in its present form is not directly applicable for the following reasons:

(1) The analytical techniques require computer programs in order to formulate solutions.

(2) The empirical data is not related to analytical procedures.

(3) The data is for structural elements under a unique loading condition or boundary condition.

(4) The data neglects effects of inertia loads, strain rate, wave propagation and/or geometry changes.

However, there are several references, most notably 20, 31, and 33 through 38 which provide information that can be incorporated into procedures that can serve as guidelines for designers. Several of the aforementioned references are texts (34 through 38) which, although primarily limited to elastic and plastic behavior, cover a wide range of structural elements such as beams, columns, plates, rings, arches and composite structure. The data in these references provide basic information regarding yield point loads and methods by which the effects of plasticity, crippling and buckling can be taken into account.

Simplified approaches for obtaining load-deflection data for crushable fuselage structure, load limiters, and beam elements are described in Reference 2. These procedures indicate that this type of approach holds promise as a method of obtaining, with reasonable accuracy, input data for more complex programs.

4.3 STRUCTURAL BEHAVIOR

There are several important aspects of a structure's behavior which can have an influence on forces that are transmitted to an occupant during a crash. Of particular concern are the failure modes, energy absorbed prior to and after failure, as well as the material properties that affect the load-deflection characteristics of the structure.

4.3.1 Failure Modes

The information presented in the literature tends to show agreement on the requirement for progressive damage in a controlled manner in order to achieve improved crashworthiness design. The structural failures which are primarily responsible for resulting in occupant injury, or fatality, are considered to be:

- Longitudinal crushing loads on the cockpit
- Vertical crushing loads on the fuselage shell
- Transverse bending of the fuselage shell
- Buckling deformation of the floor structure
- Landing gear penetration of the fuselage structure
- Rupture of flammable fluid containers
- Lateral collapse of the fuselage structure

Modifications to the structure and structural design concepts have been presented in References 3, 5, 8 and 9. Potential improvements consist of increased energy absorption capability, design for breakaway, transferral of major mass items, improved equipment tiedown, and strengthening of cabin structure. The literature distinguishes between the design for longitudinal and vertical impacts in terms of their different structural energy requirements. In the longitudinal impact, unlike the vertical impact, there exists a high-force-level energy absorption (friction) exterior to the aircraft, and the velocity change can be accomplished in a relatively long time interval.

Analysis of aircraft structural failure modes is hampered by the inability to conveniently describe large nonlinear deformations that take place during an impact in which the crash environment is complex. Aircraft behavior after impact is a function of the impact conditions and the structural characteristics of the airframe and components. Although the determination of the failure mode of various components or airframe segments provides valuable information, there exists a need to adequately describe in sequence the structural behavior and failure modes during a crash in order to develop improved design criteria. The ability to understand what is happening sequentially is an important aspect in developing a consistent approach to crashworthiness design.

References (3), (5), (8) and (9) contain information which is applicable to the areas of structural behavior and failure modes.

References (5) and (8) contain discussions regarding structural modifications which offer promise of improved survival in aircraft accidents. The contribution of the suggested modifications is reviewed in light of the influence of structural energy absorption, earth gouging and scooping phenomena, and change in effective mass upon the two crashworthiness indices:

- Extent of cabin collapse
- Floor acceleration levels

Improved structural crashworthiness in longitudinal impacts is deemed possible by:

- Reducing impulsive earth scooping
- Reinforcing cabin structure to prevent its collapse within occupiable areas
- Where practical, reducing the strength of the fuselage structure to insure failure in unoccupiable areas
- Improving energy absorption characteristics in the structure forward of the occupiable area
- Increasing deformation and energy absorption in unoccupiable areas

Improved structural crashworthiness in vertical impacts can be achieved by:

- Transferring mass from the top of the fuselage to the cabin floor
- Strengthening of cabin structure so as to increase its resistance to vertical collapse
- Modifying the cabin structure such that elastic energy absorption is increased or plastic energy absorption is provided at loads less than the general collapse load
- Increasing energy absorption in the subfloor structure realizable at load levels below the cabin collapse load

4.3.2 Energy Absorption

There is general agreement throughout the literature that the design of a crashworthy structure requires that a logical sequence of structural failure be planned. The use of seats capable of taking a high "G" loading would not be logical if the design requirements for the airframe and major mass items (i.e., high wing, engine) are such that failure could cause collapse of the occupant's liveable space, causing injury or fatality, while the seat remains intact. On the other hand, the design of an airframe sufficiently strong to hold occupants in place under high impact velocities while the airframe is undergoing very little deformation would be as undesirable as a structure which collapses easily, since the occupant would be subjected to intolerable acceleration magnitudes. The incorporation of energy absorption capability into the structure will help to alleviate the aforementioned design inadequacies since energy absorbers can serve the following functions:

- Reduce the nontolerable deceleration pulses on the occupant.
- Permit seat structures to yield to short-duration high-acceleration pulses.

Energy absorbers can be incorporated prudently throughout the airframe to improve the structure's crashworthiness capability. However, as is the case in any design solution, there exists a trade-off among performance, cost, weight and space. Thus, the use of energy absorbers to improve aircraft crashworthiness requires a determination of:

- Where energy absorption is most critically needed.
- The amount of energy absorption required.
- The effect of dynamic coupling behavior between the absorber and existing structure on responses.
- The type of energy absorber that will best serve the needs.
- The cost in terms of weight and/or space that can be tolerated.

References (3), (5), (8), (9), (10) and (11) present information which is pertinent to the subject of energy absorption.

References (5) and (8) show that the kinetic energy of the impacting aircraft is equal to the energy absorbed in deforming the soil and the structure. The controllable factors are:

- Average force developed in the collapse of the structure
- Linear deformation of the structure
- Deformation energy in structure other than the cabin. The reduction in the deceleration forces requires a corresponding increase in deceleration distance and, consequently, crushable material.

The crash environment and how it pertains to energy absorption is discussed in Reference 9. The terrain is considered to be the most important parameter in determining the causes of structural collapse. With soft ground, energy is primarily dissipated due to soil plowing or compression. However, on a hard surface, friction between the structure and surface is the primary means of dissipating energy. Energy absorbed by failure of landing gears, pods and pylons is considered to be insignificant due to their small mass relative to the total structure for longitudinal velocity impacts. For a large transport, the report concludes that kinetic energy cannot efficiently be absorbed by structural collapse and still retain a survivable shell.

In Reference (11) it is concluded that: (a) it is completely impractical, through the use of energy absorbers, to significantly reduce the longitudinal acceleration level for occupants in accidents involving a

large change in velocity in a single deceleration pulse; (b) it is practical to provide energy absorption to limit vertical acceleration in the order of 20-25G in accidents occurring at descent rates ranging from 40-50 fps, assuming some vertical deformation of the structure; (c) it is possible to reduce short-duration (.005 to .010 sec) peak loads to lower values in order to prevent seat failures due to exceedance of design strength.

From a crashworthiness design efficiency standpoint, it is desirable to have structural elements which exhibit a load-deflection curve that is approximately flat (zero slope) beyond the elastic limit, provided the maximum transmitted load does not subject the occupant to an intolerable acceleration magnitude. There are many load-limiting devices which can be incorporated for crashworthiness considerations. However, the selection of a particular device requires that a trade-off be made between performance, weight, space and cost. Table 4-1, obtained from Reference 28, compares several "one-shot" load-limiting devices for 1000-4000 pound loads. Included is a comparison of the pertinent design factors for eight different devices. "Long-term reliability" refers to the ability of the device to perform its function without benefit of maintenance throughout the life of the aircraft, while "specific energy" indicates the amount of energy that can be absorbed per pound of weight of the device.

References 1, 3, 5, and 12 through 19 also present data related to structural element energy-absorption requirements or capability. Table 4-2 (Reference 17), for example, compares energy absorption efficiencies for several different materials and methods.

4.3.3 Strain Rate Effects

If materials exhibit strain-rate sensitivity, then the effect on the load-deflection characteristics of the structure will be a change in the yield and ultimate loads. For cases in which structural materials exhibit strain rate sensitivity, an approximate accounting for this effect can be made. Several references, including (21) through (29), discuss strain

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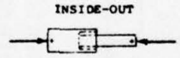
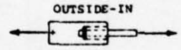
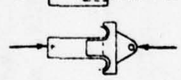
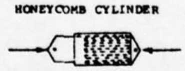
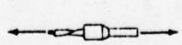
TABLE 4-1 COMPARISON OF "ONE SHOT" LOAD-LIMITING DEVICES FOR 1000- TO 4000- POUND LOADS (REFERENCE 8 TABLE 3-1)

Device Description	Energy-Absorption Process	Operation Sketch	Tension or Compression	Specific Energy (ft-lb/lb)	Space Required	Long-Term Reliability	Ability To Sustain Rebound Loads	Potential Applications
Strap/Rod over Die or Roller	Metal Bending and Friction	PLATE AND ROD  ROLLER AND STRAP OR ROD 	T	Not Known	Average	Fair to Good	Poor	Cargo Restraint
Basic Metal Tube or Plate	Elongation of Metal		T	3400-4500	Minimum	Good to Excellent	Poor[a] to Fair	Forward or Lateral Seat Braces
Basic Stranded Cable[b]	Elongation of Stainless Steel		T	3000-4500	Minimum	Excellent	Zero	Cargo Restraint[b]
"S" Shaped Bar[c]	Bending and Shear		T	1600-2400	Good	Excellent	Poor	Seat Pan Downward Support Cargo Restraint[c]
Rod Pull-Through Tube[e]	Hoop Tension and Friction		T and C	600[g]	Minimum	Good	Good	Seat Legs or Braces[e]
Inversion Tube[d]	Hoop Tension/ Compression and Bending	INSIDE-OUT  OUTSIDE-IN 	T and C	1200-2000	Average	Excellent	Excellent	Seat Legs or Braces[d]
Tube Flaring	Hoop Tension, Friction and Bending		C	30,000[h]	Average	Good	Fair[a]	Seat Pan Downward Support
Honeycomb Compression[f]	Buckling of Membrane "Columns"	HONEYCOMB CYLINDER 	C	2500-3500	Average	Good	Poor[a] to Fair	Seat Legs or Landing Gears[f]
Tension Pulley[i]	Shear and Bending of Sheave Housing		T		Excellent	Good to Excellent	Zero	Cargo or Troop Seat
Bar Through Die[k]	Torsion		T and C	746[j]	Average	Good	Fair	Seat Legs or Braces or Landing Gears
Wire Through Platen[l]	Metal Bending and Friction		T	591[j]	Average	Fair to Good	Zero	Cargo Restraint
Rolling Torus[m]	Cyclic Bending and Shear		T and C	1453[j]	Average	Good to Excellent	Excellent	Seat Legs or Landing Gear

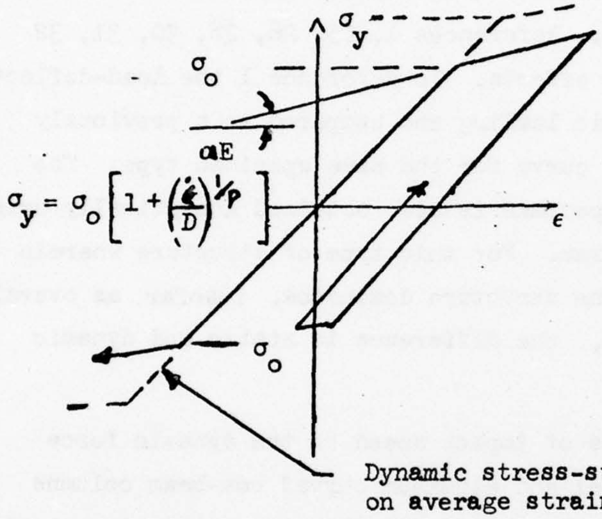
(a) This device could be rated higher if an integral rebound device were incorporated into the design.
(b) Currently being marketed by American Chain & Cable Company.
(c) Royal Netherlands Aircraft Factories Fokker did the initial development of this device in 1963.
(d) Development conducted by General Motors Research Laboratories, Warren, Michigan.
(e) A device utilizing a compressed tube rather than the expanding tube shown is being marketed by the Aerotherm Company, Bantam, Connecticut.
(f) This device is being used by the Sikorsky Aircraft Company in their S-58, S-61, and S-62 helicopter landing gears.
(g) This value is based on the compressed tube device tested. This value could be doubled in a more efficient design.
(h) This maximum value from Reference 12 does not consider end fitting weights; a value of 6000-8000 ft-lb/lb is comparable to the other devices. A device similar to this manufactured by Boeing-Vertol demonstrated specific energy of 737 ft-lb/lb.
(i) This device is manufactured by Hardman Tool & Engineering Company.
(j) Reference 18.
(k) This device is manufactured by ARDE.
(l) This device is manufactured by All-American Engineering Company.
(m) This device is manufactured by ARA, Aerospace Research Associates.

TABLE 4-2. COMPARATIVE SUMMARY OF ENERGY ABSORPTION EFFICIENCIES (REFERENCE 17)

Material or Method	Maximum Efficiency (in.lb/lb) *
Buckling Column (short)	4800
Fabric Gas Bags	72,000
Metal Gas Bags	135,000
Metal Honeycomb	130,000
Paper Honeycomb	25,000
Plastic Foam	50,000
Balsa Wood	285,000
Frangible Tubes	370,000
Stainless Steel Tension Strap	260,000
Lockheed Roll-Up Tubes With Ring Control **	450,000

NOTE: * Tabulated data are experimental values (either published information or Lockheed determined).
** Trade name "Dynasorb"

rate effects. There is no universally validated and accepted strain rate law. One approximation described in Reference 25 and used in several publications is shown below.



E = modulus of elasticity (lb/in^2)

σ_o = static value of yield point (lb/in)

σ_y = yield point (lb/in^2)

D,p = constants of the structural material

ϵ = strain (in/in)

$\dot{\epsilon}$ = strain rate (in/in/sec)

α = a plasticity factor indicating the rate of strain hardening

The approximation regards the effect of strain rate as raising the yield point (σ_y) above the static yield value (σ_o) with the associated strain hardening portion of the curve kept parallel to the static strain hardening curve.

In Reference 33 a simplified method is presented for solving impulsively loaded structure for rate-sensitive materials. The results of the study indicate that good approximations to the exact solution may be found by utilizing a rate-insensitive material with constant yield stress equal to the initial dynamic yield stress.

In general, aluminum structures do not exhibit strain rate sensitivity while steel structures are very sensitive to strain rate effects. The load-deflection behavior of structures should include this effect, where applicable, when being modeled.

4.3.4 Inertia Effects

If inertia forces for a particular type of structure are important, then the load-deflection characteristics for the structure under dynamic loading conditions can differ from the load-deflection characteristics under static loading conditions. References 1, 25, 26, 28, 30, 31, 32 present data related to inertia effects. In Reference 1 the load-deflection curve is obtained under dynamic loading and compared to a previously obtained static load-deflection curve for the same specimen type. The load-deflection curve for the specimen is also obtained analytically using an existing finite element program. For this type of structure wherein the low frequency response of the structure dominates, insofar as overall structural behavior is concerned, the difference in static and dynamic characteristics is small.

In Reference 25 the effects of impact speed on the dynamic force deflection relationship for steel and aluminum curved box-beam columns are presented. Figure 4-1 presents the load-deflection curves for steel and aluminum under static and dynamic loading conditions. As one can observe from the load-deflection curves, the analysis should be able to account for dynamic loading effects since they can differ substantially from static load-deflection characteristics for some structures.

If the higher frequency modal components dominate the response initially such as to cause failure before the fundamental mode can respond, then the effects of inertia should be considered in the load-deflection curves.

4.4 EXPERIMENTAL DATA

Correlation between test and analysis shows that the basic problem in developing analytical models is the ability to realistically describe the structural behavior under loads which will result in large deformations. The test data show that it is important that fuselage structure exhibit plastic deformation characteristics in both the longitudinal and vertical directions. Tests have shown that unless sufficient energy absorption

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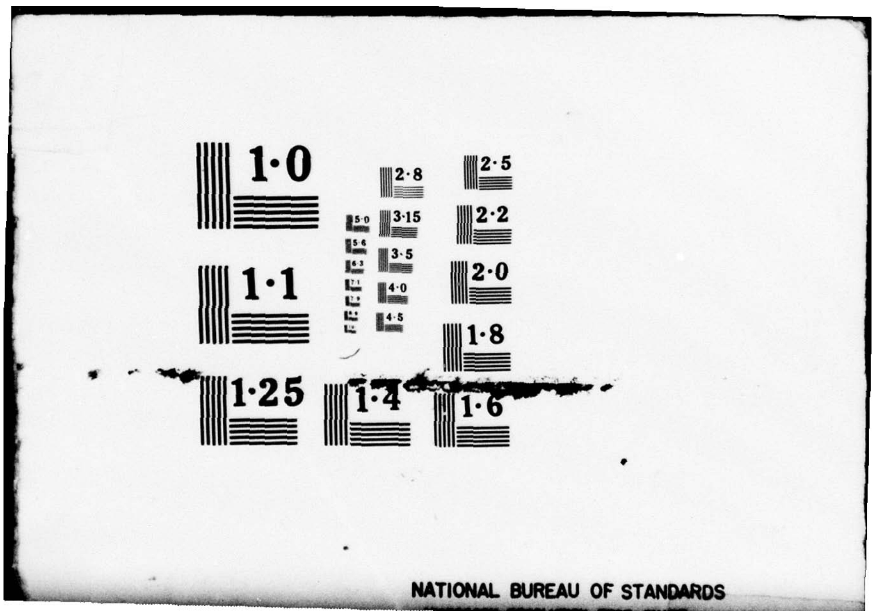
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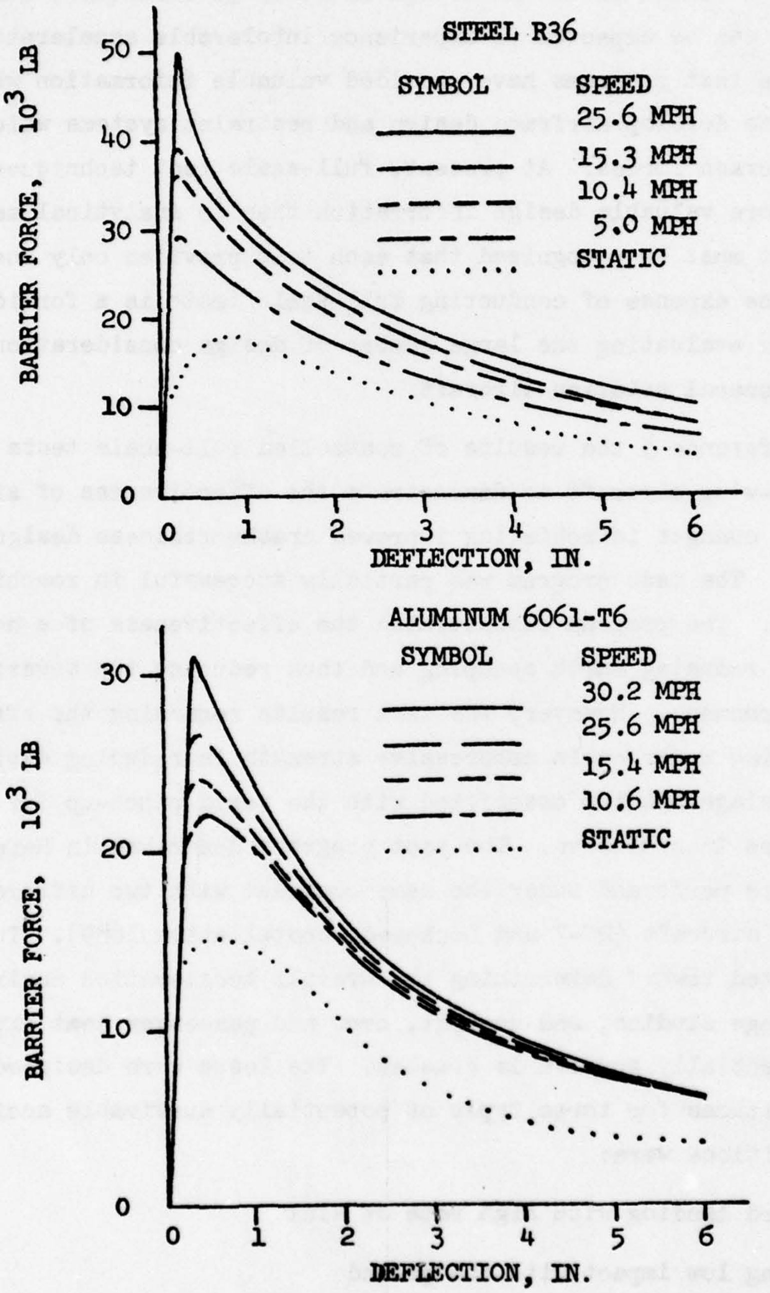

Figure 4-1. The Effects of Impact Speed on Dynamic Force-Deflection Relationship of Curved Box-Beam Columns (Reference 25)

capability is included in the design of fuselage structure, the pilot and passengers can be expected to experience intolerable acceleration forces. To date the test programs have provided valuable information which has been used to develop airframe design and restraint systems which better attenuate crash forces. At present, full-scale test techniques have provided more valuable design information than do analytical methods. However, it must be recognized that each test provides only one data point and that the expense of conducting full-scale tests is a formidable obstacle in evaluating the large number of design considerations for all types of general aviation aircraft.

In Reference 5 the results of controlled full-scale tests performed with fixed-wing aircraft to demonstrate the effectiveness of simple structural changes in achieving improved crashworthiness design are described. The test program was partially successful in reaching its objectives. The program demonstrated the effectiveness of a nose modification in reducing earth scooping and thus reducing the severity of the crash environment. However, the test results regarding the effectiveness of increasing upper cabin compressive strength in reducing cabin collapse due to fuselage bending associated with the rapid pitch-up for longitudinal crashes were inconclusive. The test programs described in References 6 and 7 were performed under the same contract with two different large fixed-wing aircraft (DC-7 and Lockheed Constellation 1649). The programs were directed toward determining the overall acceleration environment, fuel spillage studies, and cockpit, crew and passenger seat experiments during potentially survivable crashes. The tests were designed to simulate crash conditions for three types of potentially survivable accidents. The three conditions were:

- Hard landing with high rate of sink
- Wing low impact with the ground
- Impact into large trees in off-airport forced landing.

Due to a failure in the recording system, the program on the DC-7 did not meet all of the test objectives. Failure to obtain the instrument recordings represents a real and costly risk associated with full-scale test programs. Fortunately, the tests with the Lockheed 1649 which were successfully recorded showed that the structural damage and deformation of the fuselage that occurred in the crash were relatively mild, particularly in the occupiable portion. The damage in these tests were most severe in the lower forward fuselage where primary impacts were concentrated.

References 1,2, 3, 12, 14, 16, 17, 19, 21, 39 and 40 present results of tests. The data is generally in the form of load versus deflection, force versus time and stress versus strain. Reference 1 static and dynamic test results showed that for some typical aircraft structure, the energy absorbing characteristics are the same for both static and dynamic loading conditions. Figure 4-2 shows a comparison of the results of the static and dynamic tests described in Reference 1.

In Reference 3, load-deflection curves for plate stringer panel configurations are presented. The results of these panel tests, illustrated in Figure 4-3, show the energy to area ratio of the three configurations. Of particular importance are the relative absorption capabilities of the panels and their respective modes of failure. For example, the integrally machined panels produce a reasonably efficient energy-area ratio, but the load stroke performance is poor because the mode of failure is an explosive fracture in which the riser splits completely off the skin. In addition, the peak load of this latter configuration is much higher than the peak load for the other panels, which could result in higher transmitted loads. In Reference 3 the load-deflection data for the lower frame of a typical fuselage segment obtained from drop tests is also presented. This test data is compared to analysis and is shown to differ substantially. In Reference 40 the data regarding buckling characteristics of perfect and imperfect circular cylindrical shells subjected to dynamic axial loading is presented. Close agreement was found between theory and experiment for both dynamic buckling strength and buckling mode shapes.

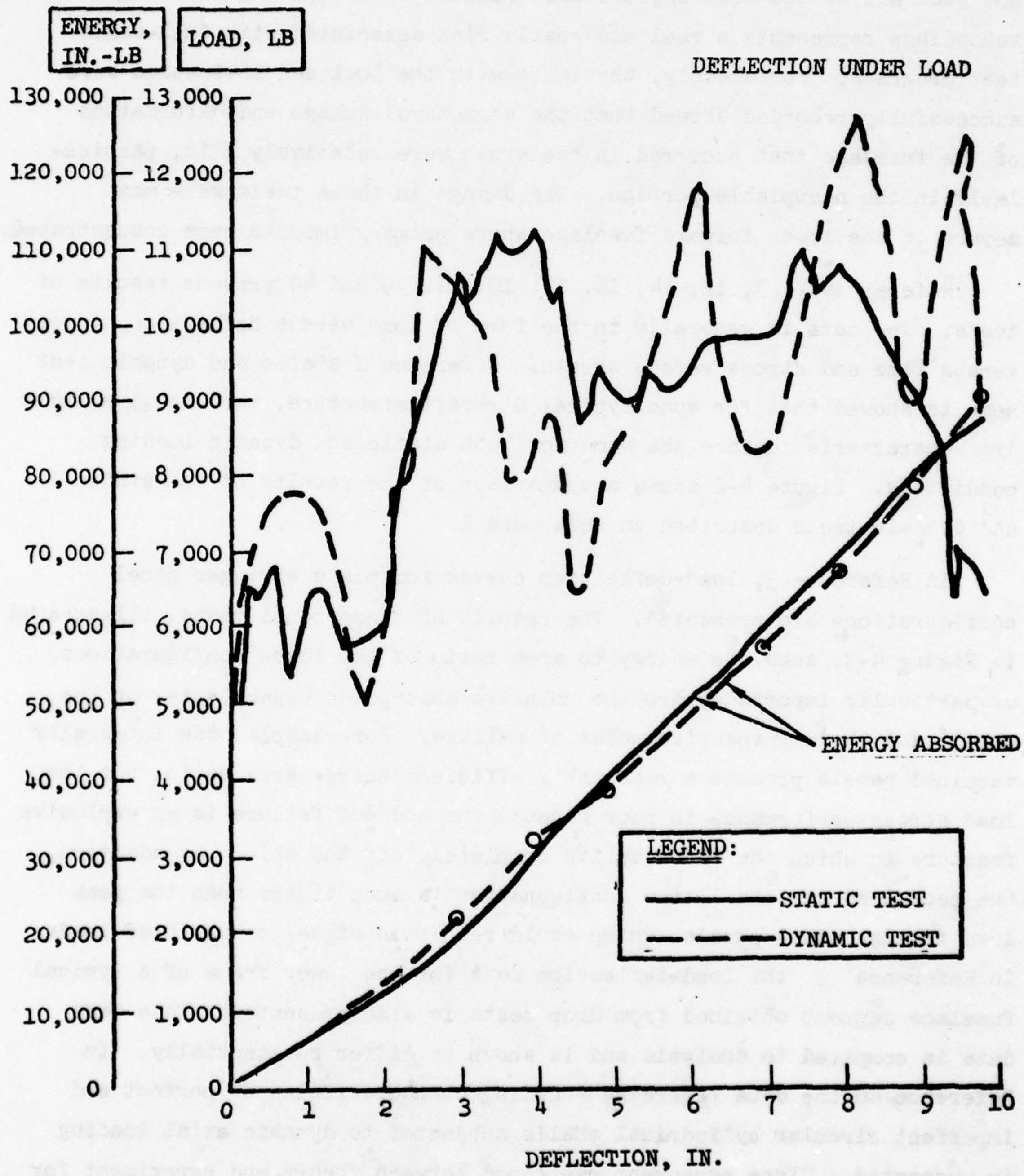

Figure 4-2 Load-Deflection and Energy-Absorbed Results for Static and Dynamic Fuselage Bumper Tests (Reference 1)

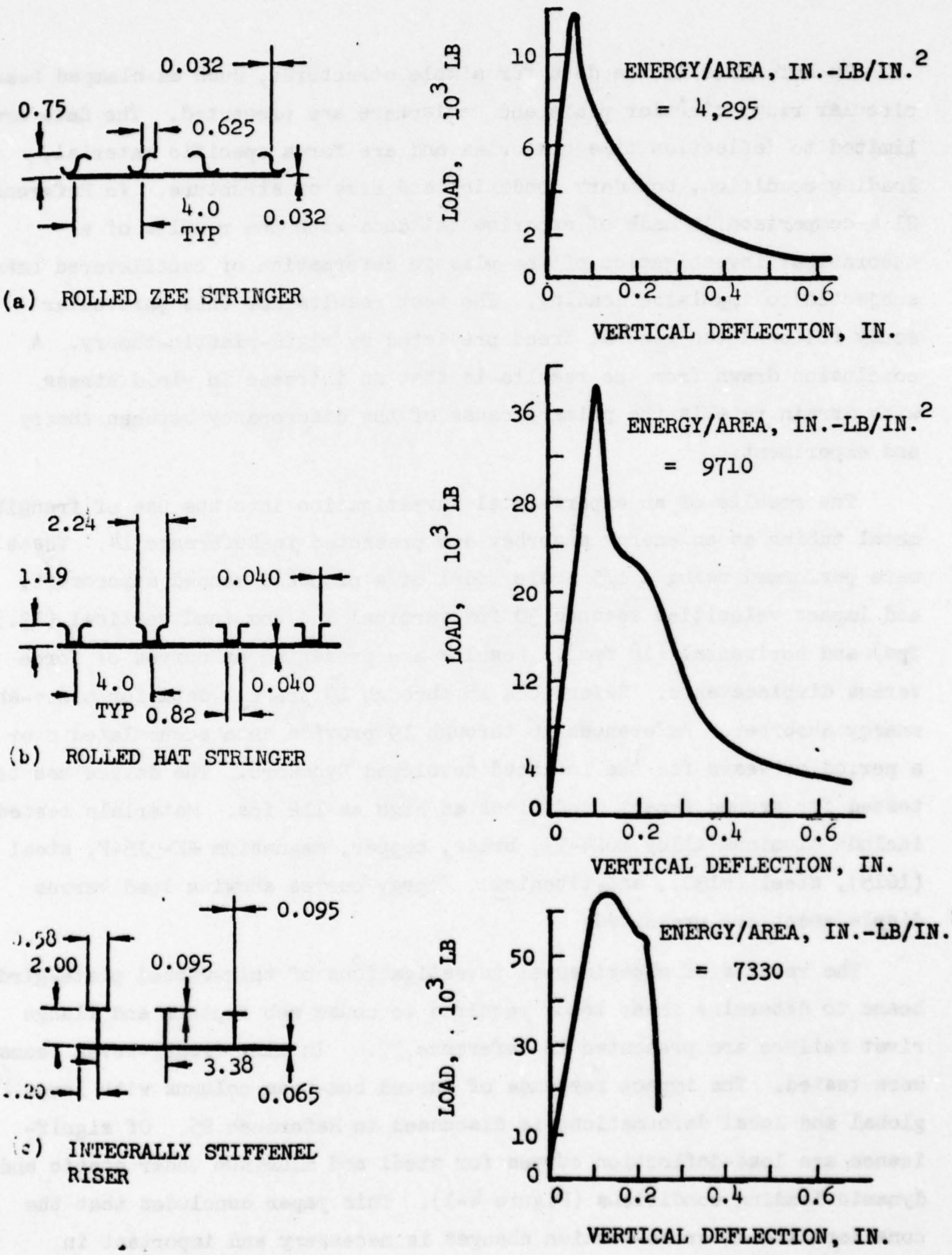

Figure 4-3. Plate Stringer Compression Panels Load-Deflection Test Data (Reference 3)

In Reference 12 the data for simple structures, such as clamped beam, circular ring, circular plate and hemisphere are presented. The data are limited to deflection time histories and are for a specific material, loading condition, boundary condition and size of structure. In Reference 21 a comparison is made of experimental data with the results of a theoretical investigation of the plastic deformation of cantilevered beams subjected to impulsive loading. The test results for this particular study followed the general trend predicted by rigid-plastic theory. A conclusion drawn from the results is that an increase in yield stress with strain rate is the primary cause of the discrepancy between theory and experiment.

The results of an experimental investigation into the use of frangible metal tubing as an energy absorber are presented in Reference 14. Tests were performed using a 1/5 scale model of a proposed manned spacecraft, and impact velocities reached 30 fps vertical and combined vertical (13.5 fps) and horizontal (18 fps). Results are presented as curves of force versus displacements. References 15 through 19 present data for a one-shot energy absorber. References 16 through 19 provide data accumulated over a period of years for the Lockheed developed Dynasorb. The device has been tested for ground impact conditions as high as 112 fps. Materials tested include aluminum alloy 2024-T3, brass, copper, magnesium AZ-31B-F, steel (1015), steel (4130), and titanium. Energy curves showing load versus displacement are presented.

The results of experimental investigations of thin-webbed plate-girder beams to determine shear loads required to cause web rupture and flange rivet failure are presented in Reference 32. In all, twenty-seven beams were tested. The impact response of curved box-beam columns with large global and local deformations is discussed in Reference 25. Of significance are load-deflection curves for steel and aluminum under static and dynamic loading conditions (Figure 4-1). This paper concludes that the consideration of cross-section changes is necessary and important in predicting the impact response of beam columns with thin-walled box

sections subjected to large deformation. The effects of strain rate sensitivity and strain wave propagation on the load-deflection curve are discussed.

Stress-strain curves for aluminum honeycomb and two foamed plastic structures are presented in Reference 42. The characteristics of these three materials are examined to ascertain how they can be applied for human protection against accelerations encountered at low impact speeds (30 fps). Reference 41 presents data regarding modes of failure of multiweb beams. The ultimate strength and buckling characteristics of multiweb beams have been investigated both experimentally and theoretically. The three primary types of instability that occur are (1) local buckling, (2) wrinkling, and (3) interrivet buckling. It is noted that beams of solid cross sections typically exhibit large plastic deformations as shown in Figure 4-4, while built-up sheet beams exhibit structural behavior similar to that shown in Figure 4-5.

Although much effort has been expended to obtain structural characteristics of structural elements, only a small percentage of published data provides load-deflection data that can be directly incorporated by designers. Table 4-3 shows a cross section of data available from the reference material. The load-deflection data provides some useful data to the designer, in that characteristic trends can be associated with different types of structural elements. For convenience three categories depicting load-deflection behavior have been identified. The load categories indicate that in the post-failure region the behavior of structure can be grossly defined as increasing, constant or decreasing load with deflection. The actual characteristics may vary widely as shown in Figures 4-1 through 4-5. Table 4-4 presents a matrix of structural element load-deflection categories and load types. The table indicates, to some degree, how the selection of a structural element design can influence the loads that will be experienced in an aircraft. This information, without additional data such as energy-absorption efficiency, linear load-deflection curves, and yield points for specific design configurations, although

TABLE 4-3. LOAD-DEFLECTION DATA (REFERENCE 1)

Structural Element Type	Test Data		Load-Defl. Curves		Load Category*	Loading	Reference
	Static	Dynamic	Static	Dynamic			
Shell segment on bulkhead support	X	X	X	X	1	Compression of skin (bending and tension on bulkheads)	1
Metal tube or stranded cable	X	X	X	X	2	Tension	2
Inversion tube	X	X	X	X	2	Tension (outside-in) Compression (inside-out)	 2
Tube flaring					2	Compression	2
Honeycomb					2	Compression (buckling of membrane columns)	2
Plate stringer							
a) rolled zee		X		X	3	Compression	3
b) rolled hat		X		X	3	Compression	3
c) integrally machined stiffener		X		X	3	Compression (skin buckling and bending of risers)	3
Box beam-column	X	X	X	X	3	Compression	23
Foamed Plastic		X		**	2	Compression	42
Frangible tube	X	X	X	X	*** 1,2	Compression	13, 14, 16 17, 19

* LOAD CATEGORIES
1. Increasing load with increase in deflection
2. Constant load with increase in deflection
3. Decreasing load with increase in deflection

** Data in form of stress versus strain and load versus time

*** Inadequate control ring design results in load increase versus deflection

TABLE 4-4. MATRIX OF STRUCTURAL ELEMENT LOAD-DEFLECTION CATEGORIES AND LOAD TYPE (REFERENCE 1)

Load Type	Load Categories *		
	1	2	3 **
Compression	Skin-Stringer Coil Spring Stiffened Cylinder	Frangible Tube Telescoping Tube Honeycomb Multiple Cell Structure Short Column	Sheet Skin Flat and Curved Plate Axially Loaded Cylinder Slender Long Column Stringer Shell Segment Beam
Tension	Bulkhead Stiffener	Inversion Tube Stainless Steel Strap Stranded Cable	Short Elongation Strap Sheet Skin Stringer

* LOAD CATEGORIES

1. Increasing load with increase in deflection
2. Constant load with increase in deflection
3. Decreasing load with increase in deflection

** Compression members tend to fail as a result of the lateral bending induced by the compression load, an action which is commonly called buckling.

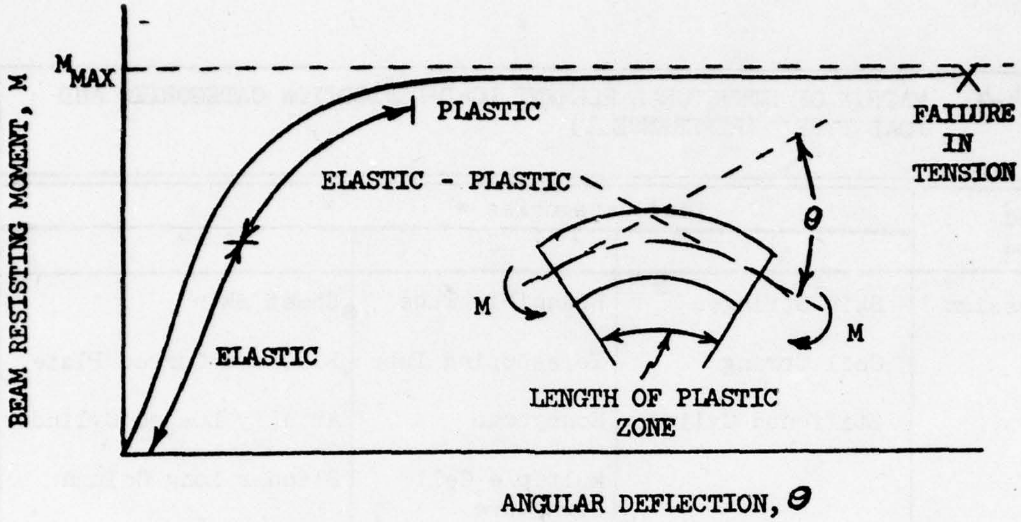

Figure 4-4. Structural Behavior Typical of Solid Cross-Section Beams of Ductile Material (Reference 41)

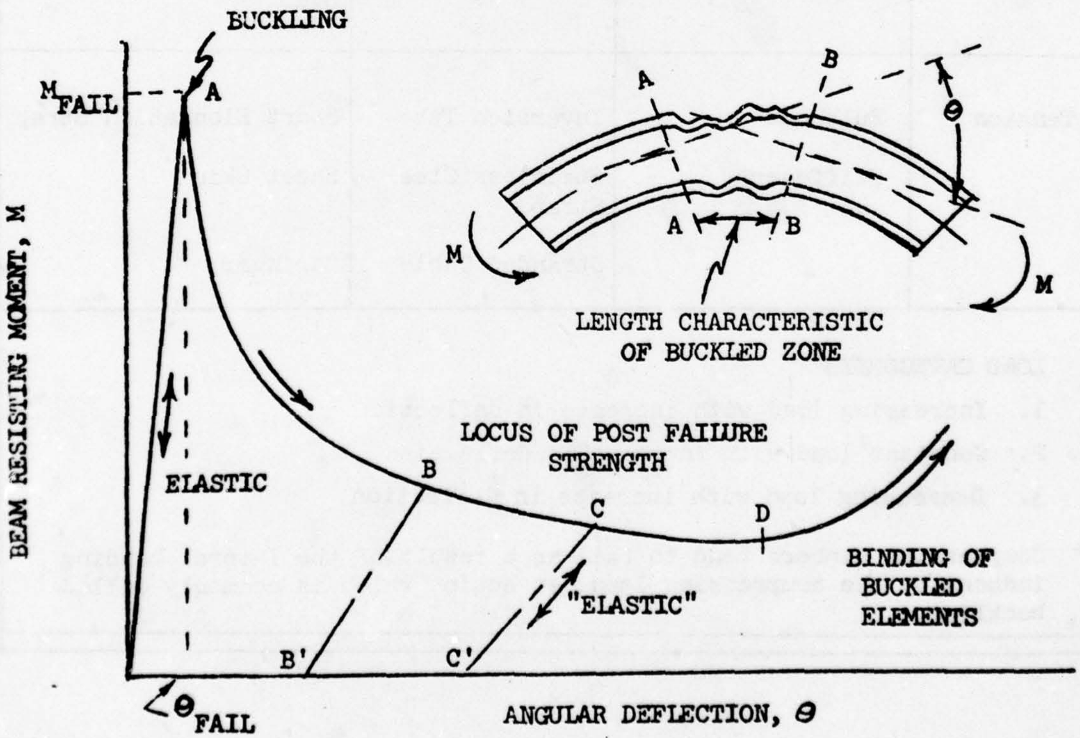

Figure 4-5. Structural Behavior Typical of Built-up Beams (Reference 41)

a contribution, is inadequate for crashworthiness design. References 34, 35, and 38 present some valuable data concerning various types of structural elements up to the point of failure and including plasticity effects. Of particular importance in this data is that nondimensional graphs are presented; these allow one to easily determine load capability for different geometry or end constraints. Reference 34 includes discussions of plastic bending, buckling of flanges and webs, lateral buckling of beams, buckling of beams in combined axial compression and bending, buckling of frames, and a general method for computing elastic-plastic displacements. Reference 35 presents discussions and tables of data for determining load and deflection for beams and frames, including simultaneous axial and transverse loading, variable cross sections and curved sections, flat plates (ultimate strength, large deflections, nonuniform loading), columns (eccentric loading, combined compression and bending), and buckling of bars, columns, flat and curved plates. Reference 38 provides a discussion of the design of members in tension (skin, stringers, spar caps), bending (beams), torsion (shafts), compression (columns, flat plates, curved sheets), and shear (webs). Included in this reference are design equations, nondimensional buckling design curves, and a discussion of the manner in which local crippling failures can be analyzed.

Substructure static and dynamic tests performed with integrally stiffened sheet metal/stringer type structure are described in Reference 2. This type of structure is representative of aircraft lower fuselage structure. The test results indicate that, for these types of structural elements, static testing to determine load-deflection characteristics should yield sufficiently accurate results when compared to dynamic test results, but in a more economical manner. A static test, in addition to being more economical to perform than a dynamic test, has the advantages of easier and more precise alignment of impact head with specimen, a more rapid test setup and, generally, a lesser amount of instrumentation required. However, a dynamic test has the advantage that the amount of springback from the maximum deflected value is immediately evident. With a static test, the structure will relax slowly to its permanently deformed position. For general aviation aircraft impact conditions, the springback could easily reach 50 percent of the maximum deflected value in the cabin region.

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SECTION 5

STRUCTURAL CRASHWORTHINESS DESIGN AND COMPLIANCE METHODS

5.1 INTRODUCTION

The purpose of this section is to present the factors that influence the formulation of a satisfactory structural crashworthiness design and to describe the manner in which these factors can be considered. In addition, methods by which compliance to crashworthiness requirements can be shown are presented. A systems analysis approach to aid in the development of consistent crashworthiness designs is presented. The information presented is general enough in concept that it applies to all types of general aviation airplane designs and crash conditions.

5.2 SYSTEMS ANALYSIS APPROACH TO A CONSISTENT CRASHWORTHY DESIGN

The objective of a satisfactory crashworthy design is occupant survivability which implies that:

- The structure containing the habitable space will not collapse sufficiently to impinge upon the occupant.
- The structure will crush and deform in a predictable, controlled manner, minimizing the forces imposed upon the occupants.
- The occupant will be protected from lethal blows as a result of contact with hardware.

The development of structural crashworthiness design criteria that will be of substantial benefit to potential users should take into consideration those factors that influence the severity of injury an occupant will experience during a crash environment as well as to stipulate the manner in which acceptable crashworthiness capability can be ascertained. This means that the significant factors which contribute to the development of successful

structural crashworthiness design criteria for severe, yet survivable, accidents include:

- The definition of the probable crash environment.
- Methods of analysis to facilitate the incorporation of structural crashworthiness features early in the design phase.
- Human tolerance limits and measures of injury potential.
- Load-deformation characteristics of the major structural elements for existing and future airplane design.

The use of rational design procedures will enhance the effectiveness of crash design criteria thatare developed. The design of the various parts of a vehicle should be consistent in the sense that the proper interface is maintained among the essential structural elements, masses and occupant restraint system. Furthermore, a rational approach should also include the influence of structural weight and configuration considerations in the procedure by which an acceptable crashworthy design is achieved. Figure 5-1 illustrates a rational approach to the development of structural crashworthy design criteria. The approach outlined in Figure 5-1 includes the influencing factors, and if utilized properly would result in a consistent design which maintains the desired compatibility among the various structures.

From Figure 5-1 it can be seen that the landing gear and crushable structure between the impact point and the seat support is the first area of interest in developing a crashworthy design. Loads resulting from deformation of the structure in response to a given impact speed and attitude are compared with the occupant tolerance to acceleration magnitudes, durations and rates of onset. Providing strength in this area is beneficial up to a point. Should the load levels during the fuselage crushing mode exceed those which can be tolerated by the occupant, then the energy absorbed does not serve a useful purpose because the occupant does not survive.

Although the maximum strength of the occupant seat support and harness should ideally match the tolerance of the occupant, a consistent design

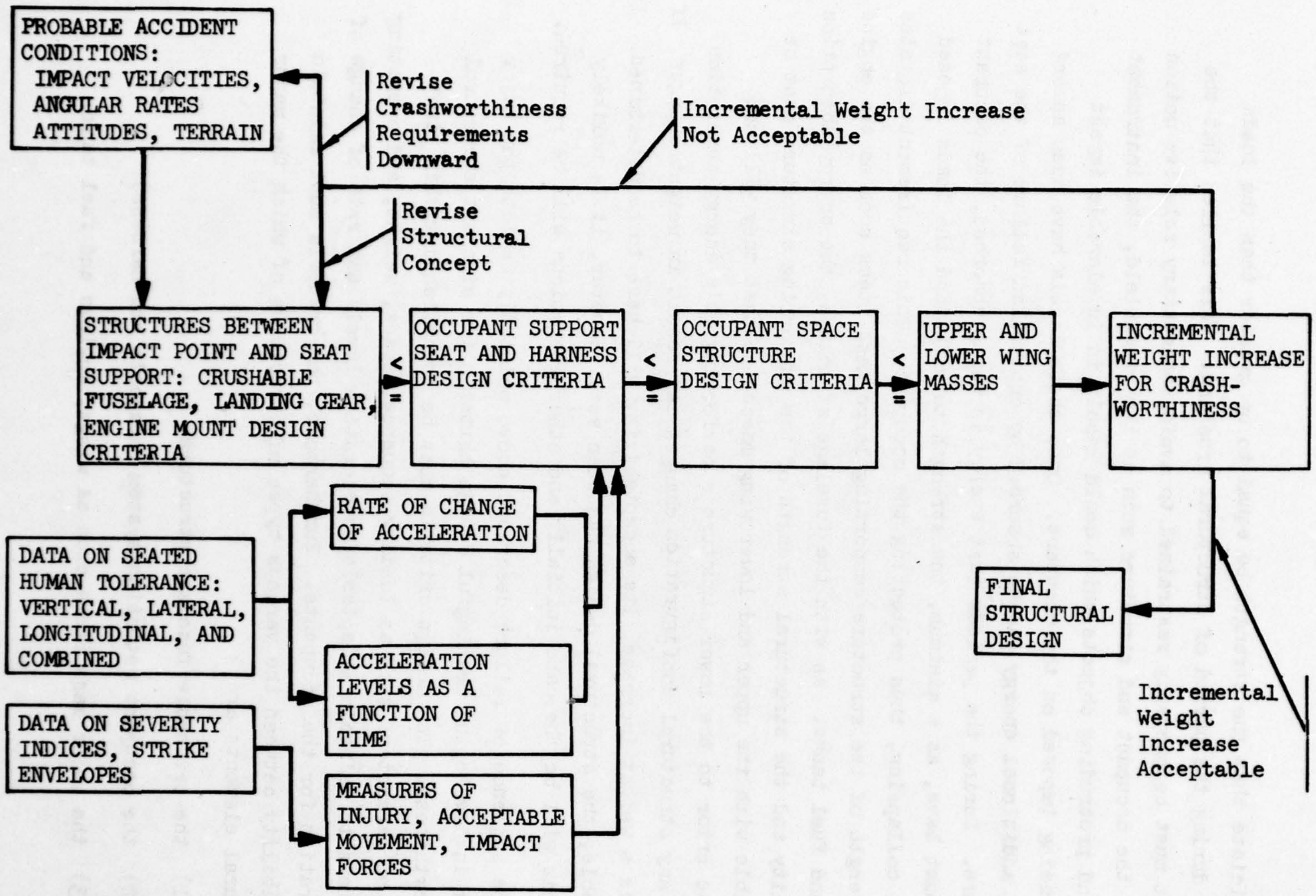

Figure 5-1. Consistent Crashworthiness Design Criteria Approach

would dictate that the strength be equal to or greater than the loads imposed during the period of structural crushing. This implies that the occupant must be properly restrained to avoid unnecessary relative motion between the occupant and structure such as the windshield, the instrument panel and protruding objects which could result in intolerable impact forces being imposed on the occupant. Once these levels have been ascertained, additional energy can be absorbed by controlled failure of the seat structure. During the periods that energy is being absorbed, the occupant space must have, as a minimum, the strength to withstand the loads imposed without collapsing, thus protecting the occupant. This requirement dictates the strength of the structure supporting large mass items such as the engine, wings and fuel tanks. As with the fuselage structure, the energy absorption capability and the structural strength of the supporting structure must be compatible with the upper and lower wing masses so that they will not collapse prior to the lower structure's performing it's energy absorption work. Any structural configuration changes can result in weight changes. If there is a weight increase, its acceptability will have to be determined. If acceptable, the structural design has been set. However, it is unlikely that this will be the case initially and other iterations will be required.

The sequence of failure described above pointedly depicts the major problem in developing meaningful design criteria for aircraft structural crashworthiness. The design criteria must be established within limitations on parameters such as loading sequence, space, weight, and operating parameters to maintain acceptable acceleration levels and rate of change of acceleration for the occupants. Furthermore, the criteria must maintain compatibility between the various types of structures of which the major structural elements are:

(1) the crushable fuselage structure

(2) the occupant retention system (seatbelt and harness)

(3) the major mass items such as wings, engines and fuel tanks

5.3 METHODS FOR DEMONSTRATING COMPLIANCE

5.3.1 General

In the development of design criteria, certain considerations should be satisfied in order to enhance their acceptance. These are:

- Methods should be available by which the criteria can be satisfied.
- Methods that are available should take into account the various approaches to preliminary and final design used by the industry.
- Methods should be practical and not impose unrealistic requirements
- At least two methods should be made available so that designers can select on the basis of compatibility with their particular design processes.

This section describes the manner in which available environmental, structural and design data can be used to show compliance with design criteria. Included is the use of an iterative procedure to show how a satisfactory crashworthy design can be evaluated and achieved with the minimum weight penalty. Several methods of different complexities, for showing compliance with criteria, are presented.

5.3.2 Preliminary Design

Normally, during the initial stages of a design, the structural information that is available consists of a general layout, vehicle weight and c.g. position data and some new structural concepts. In some instances, particularly for completely new design, this information can be very limited. However, in most situations only limited design changes are made in selected regions affecting a small portion of the structure. For example, depending on weight and mission, many airplane manufacturers perpetuate some design features (engine mount arrangement, or one, two or three spar wing construction) either because of economics, past success and/or familiarity with certain concepts and procedures. Even when confronted with the minimum available data, the performance of a crash analysis during preliminary design can be beneficial because at this stage the design is reasonably flexible. Thus, desirable crashworthy features can be incorporated more economically than during the latter stages of design.

How then does the designer approach the problem of evaluating the crashworthiness capability of an airplane that is on the drawing board? With the use of Figure 5-2, the iterative process can be used to determine an acceptable crashworthy design, taking into account the crash environment, an available analytical method, structural load-deflection behavior, structural design and occupant tolerance criteria as well as potential weight and space penalties. An initial set of available data is used to obtain responses of structure and occupant to a specified crash environment. The structural responses are compared to an existing design criteria (i.e., restraint system, cabin, equipment, mass penetration). The occupant response is compared to existing tolerance criteria (human tolerance, strike envelope, impact force) and an assessment is made of the probability of a serious fatal injury.

It may well be that the governing structural design and occupant tolerance criteria are inter-related (i.e., cabin volume change and occupant strike envelope). If the analysis shows either the structural design criteria or occupant tolerance criteria is exceeded, then the structural characteristics of the proposed design indicate what changes are in order. For example, abrupt failures in some areas pose a threat to the occupiable volume and may be avoided with a change in concept or material, providing more plastic deformation. The designer can alter some of the initial concepts and the analysis can then be performed with changes in load-deformation characteristics to determine what, if any, improvement has been achieved. It may be that the improvement in crashworthiness may come from better restraint system concepts and not structural changes. If so, then this should still be determined within the framework of the iterative procedure.

Available techniques for assessing occupant chances of survival are presented in Section 3. Structural load-deflection behavior is presented in Section 4. The procedure presented in Figure 5-2 is not dependent on structural and occupant assessment being performed within the same analysis. More likely there will be a requirement for a minimum of two integrated analytical methods, one for a structural model and one for an occupant-seat-restraint system model. Several occupant models are described in References 1 through 5.

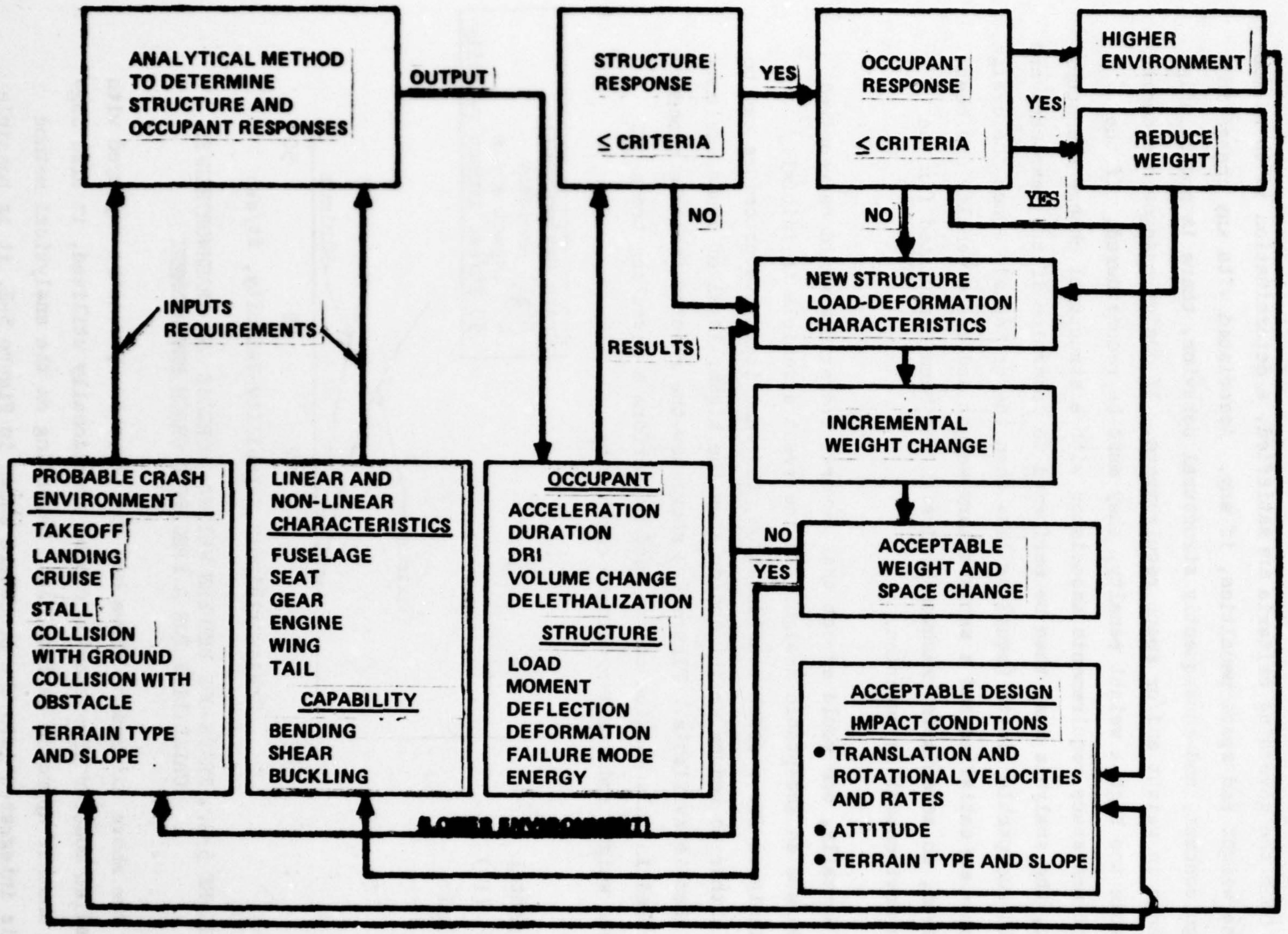

Figure 5-2. Procedure For Assessing a Structural Crashworthiness Design

Once the governing criteria are satisfied, a determination is to be made of the weight and space penalties, if any. Associated with any change in design concept, and consequently structural behavior, there is potentially a change in weight and/or space requirements. If design changes are deemed to cause too high a weight penalty, they must be reconsidered. If the weight and space requirements associated with a structural change are acceptable, the analysis must then be performed to determine if the responses are within acceptable limits (equal or less than the criteria). Once the design criteria are satisfied and a satisfactory weight and space penalty has been achieved, an acceptable crashworthy design has been formulated for the crash environment in question.

Normally, one would expect that several iterations would be required to achieve an acceptable design. In the event a vehicle is initially overdesigned for a crash consideration, the same iterative procedure can be used either to reduce weight and/or show the higher level of crash environment that is available. Figure 5-3 shows how the results from the procedure described in this section can be used to perform a revealing trade-off between weight and crashworthiness capability.

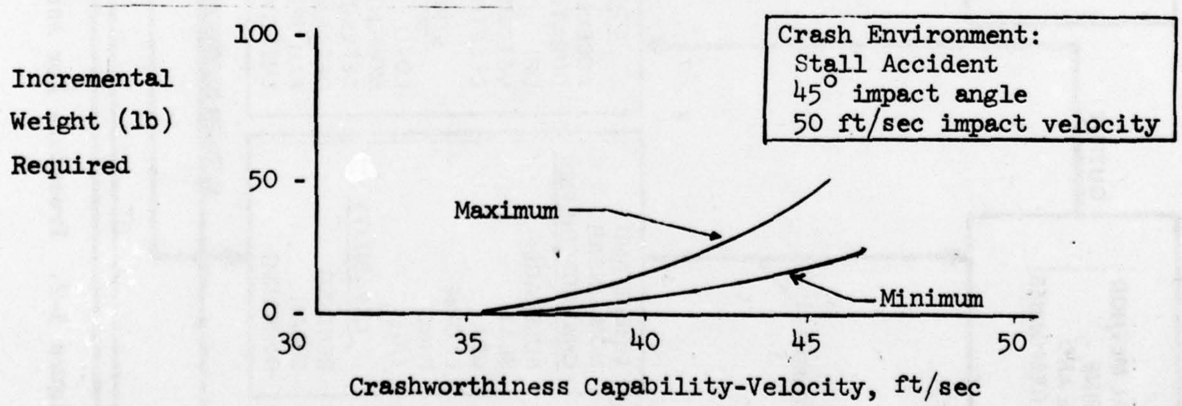

FIGURE 5-3. TRADE-OFF BETWEEN WEIGHT INCREASE AND CRASHWORTHINESS CAPABILITY FOR A SPECIFIED CRASH ENVIRONMENT

While the above discussion shows how the iterative procedure employed with a detailed model representation can be functionally utilized, it also suggests another approach is feasible. Depending on the analytical method that is integrated into the procedure shown in Figure 5-2, it is possible

to reverse the modeling process, in a manner of speaking, and "stipulate" the load-deformation behavior that is required to meet a specified energy absorption level for a probable crash condition. Following the procedure described earlier in this section, the stipulated requirements would have to be shown to result in an acceptable design. Once verified, the designer would then have to select structure with appropriate load-deflection characteristics. This technique would also provide data to perform a weight versus crashworthiness capability tradeoff as shown in Figure 5-3.

Controlled crash testing of complete airframes as a means to show compliance with design criteria is prohibitively costly and unrealistic. At best each test provides only one data point. Furthermore, a design which is considered unacceptable requires modification and additional test verification. An alternative to such crash testing is the use of analytical procedures or some combination of analytical procedures coupled with limited experimental verification. The experimental verification could be performed to show that; 1) methods that were applied are valid, or 2) provide justification for the use of selected data. Consequently, testing could be limited to structural elements or substructures.

5.4 REFERENCES

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